Exploring dark sectors at low-energy colliders

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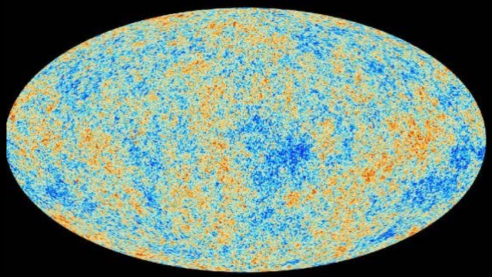
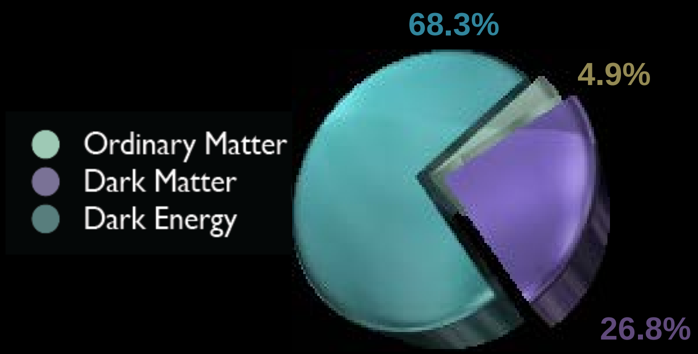
SLAC experimental seminars
SLAC – December 2013

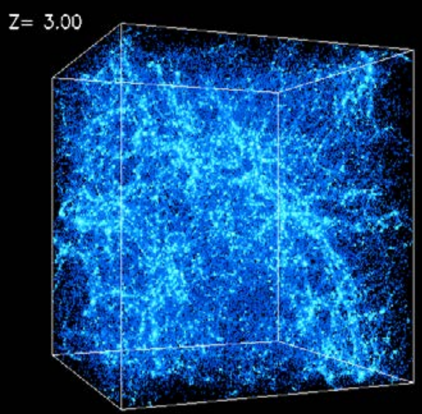
Dark matter

Lensing

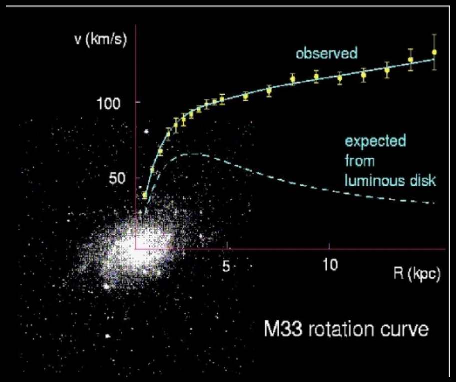
CMB



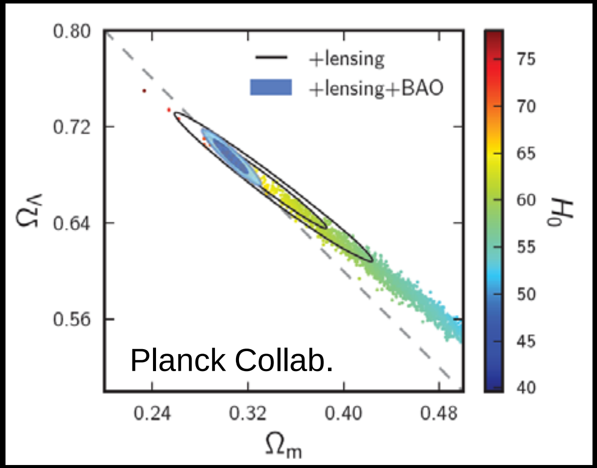




Structure

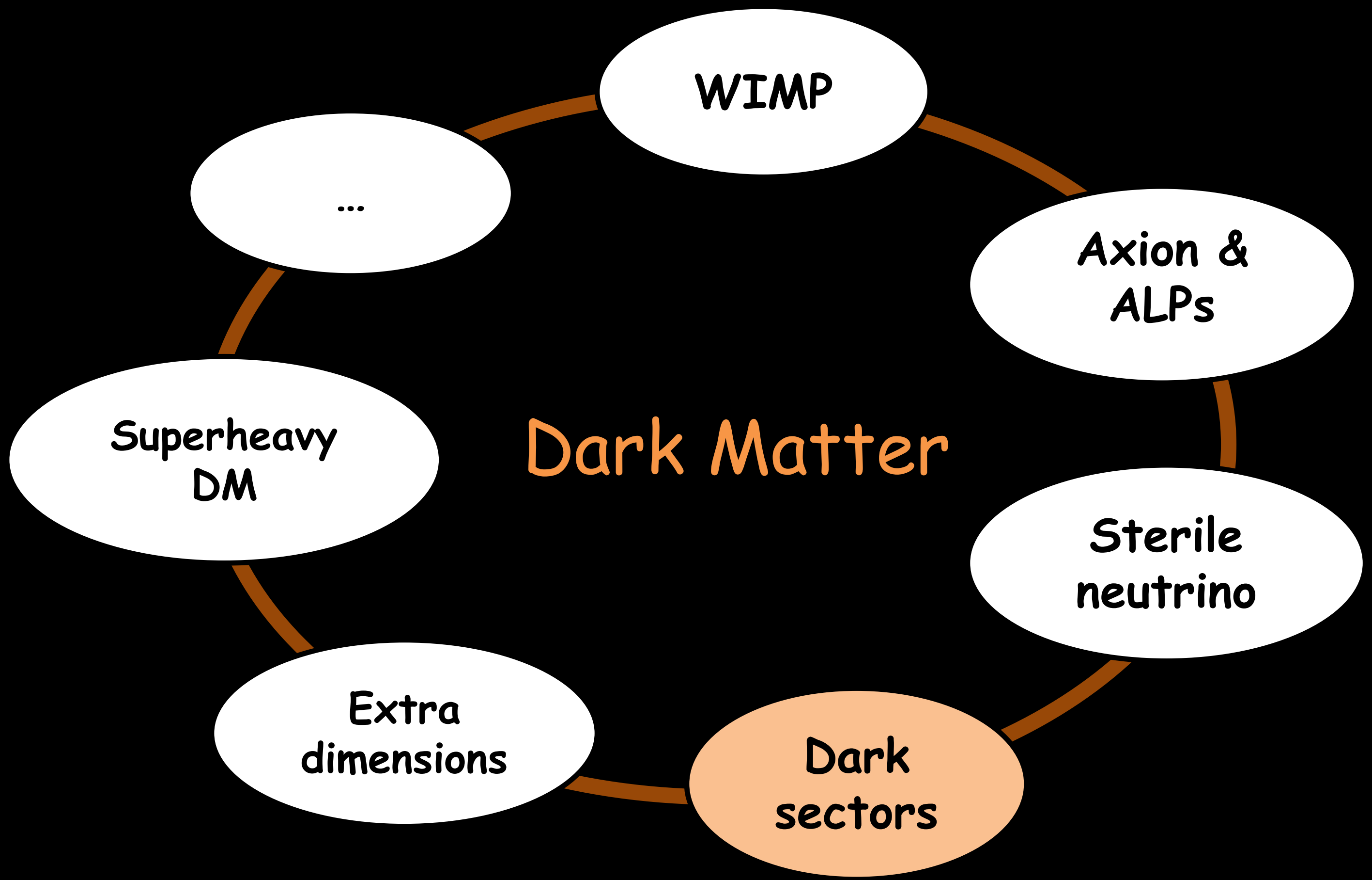


Rotation curve



We know dark matter exists, but its nature remains unknown !

A dizzying list of candidates…



Recent results from the LHC and direct detection experiments "challenge" the traditional WIMP paradigm and motivate the exploration of new ideas.

A new possibility – dark sectors

- Recent anomalies observed by satellite and terrestrial experiments have motivated dark matter models introducing a new sector with a 'dark' force mediated by a light gauge boson.
- Implications for astrophysics, cosmology and particle physics.
- In particular, low-energy colliders and fixed target experiments offer an ideal environment to probe these new ideas.

Notation confusion

dark sector = hidden sector = secluded sector

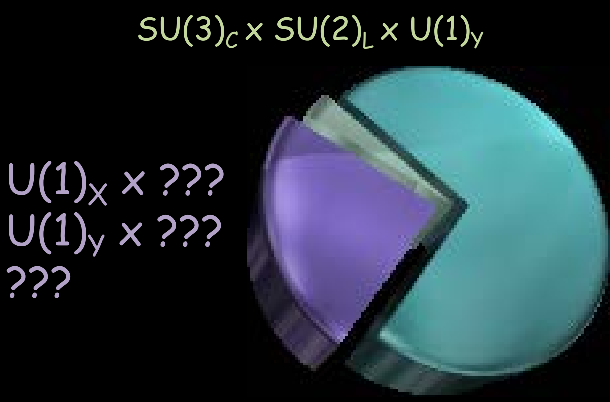
dark photon = hidden photon = secluded photon
A' = U-boson = γ_D

(I'll try to be consistent…)

Dark sectors

There might be dark sectors

- New sectors that don't couple directly to the Standard Model.
- Theoretically motivated: string theory and many BSM scenarios include dark sectors with extra U(1).
- Holdum's question ('86) : are there additional U(1)? (PLB 166 (1986) 196)
- Dark photons (A') are the corresponding U(1) gauge bosons, mediating this dark force.



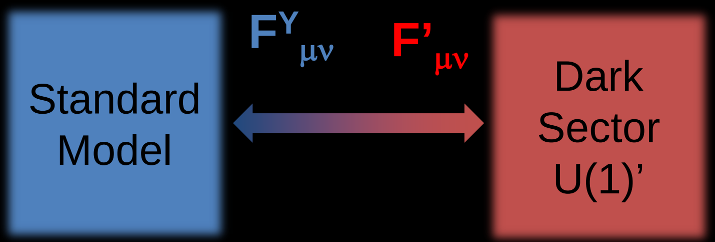
Dark matter could be part of a dark sector

- Dark matter and other new particles may reside in dark sectors.
- Could have a very rich structure.

How could we detect them?

- Interaction between dark sector and SM occurs through high-dimension operator, often referred to as "portals". At low-energy, the "vector portal" is dominant.

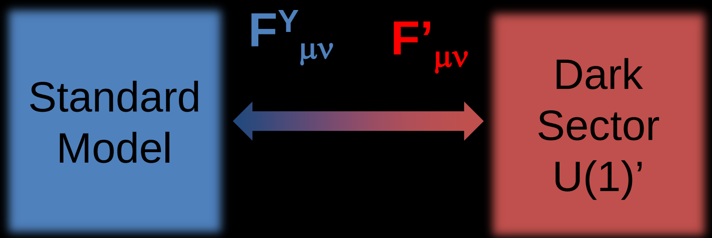
- Dark sector with a new U(1)’
- Interaction dark sector - SM via kinetic mixing between the hypercharge and U(1)’ fields with a mixing strength ε



$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

Holdom, Galison, Manohar

- Dark sector with a new U(1)'
- Interaction dark sector - SM via kinetic mixing between the hypercharge and U(1)' fields with a mixing strength ε
- After EWSB, there is a coupling $\varepsilon' e A' J_{EM}$ between the dark photon and EM charged particles (also with the Z).
- In other words, there is a dark photon – SM fermion coupling $\alpha' = \varepsilon^2 \alpha$.

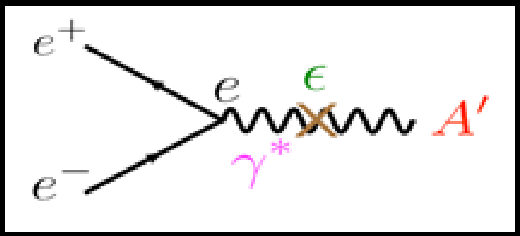


$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

↓ EWSB

$$\Delta\mathcal{L} = \frac{\varepsilon'}{2} F^{EM,\mu\nu} F'_{\mu\nu} \quad (+Z)$$

$$\varepsilon' = \varepsilon \cos\theta_w$$



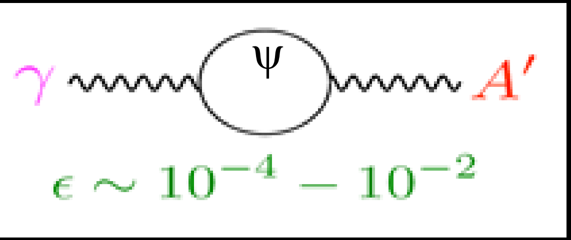
Dark sector and vector portal

- Dark sector with a new U(1)'
- Interaction dark sector - SM via kinetic mixing between the hypercharge and U(1)' fields with a mixing strength ε
- After EWSB, there is a coupling $\varepsilon' e A' J_{EM}$ between the dark photon and EM charged particles (also with the Z).
- In other words, there is a dark photon – SM fermion coupling $\alpha' = \varepsilon^2\alpha$.
- Mixing can be generated by perturbative effect, strength typically $\varepsilon \sim 10^{-5} - 10^{-2}$, but could be smaller.
- Theoretical prejudice for a mass scale $m_{A'} \sim \sqrt{\varepsilon}\, m_{EW} \sim$ MeV – GeV,

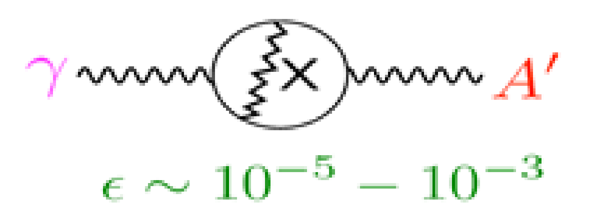
Any evidence for such a scenario?

Mixing can be generated by perturbative effect, e.g.

heavy particle ψ with both dark and EM charges.



GUT (2 loops)

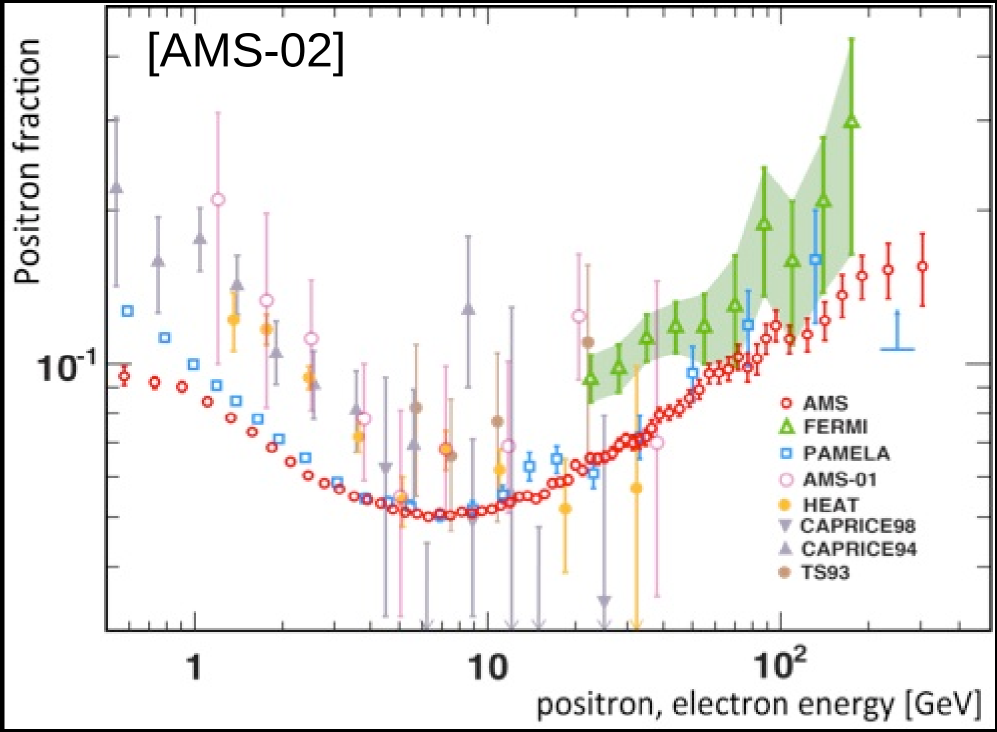


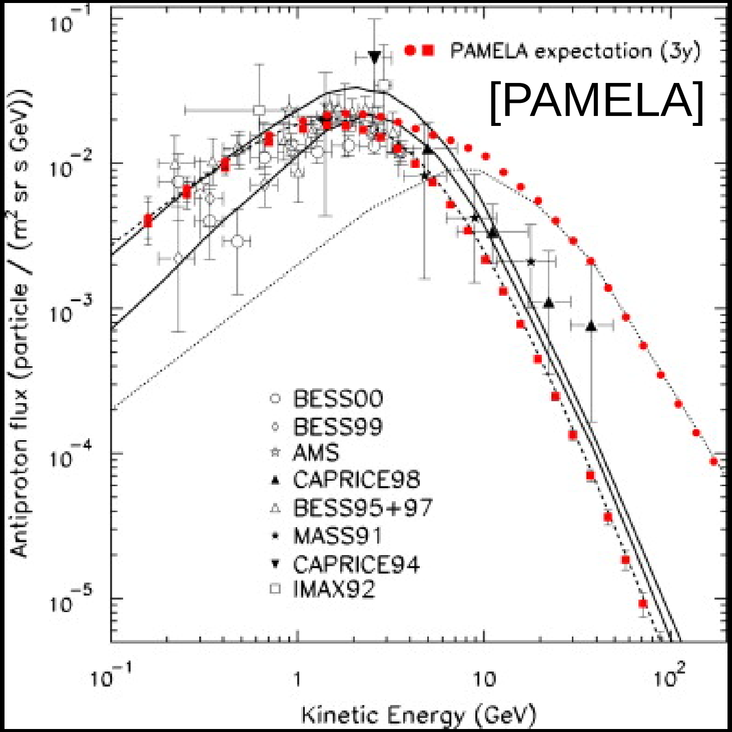
($\rightarrow 10^{-7}$ if both U(1)'s are in unified groups)

e.g. Arkani-Hamed & Weiner;
Cheung, Ruderman, Wang, Yavin;
Morrissey, Poland, Zurek;
Essig, Schuster, Toro;

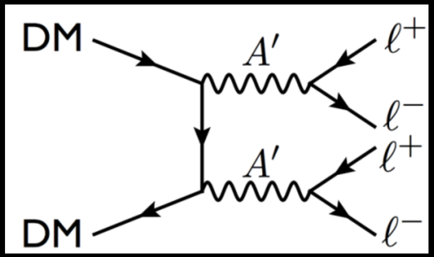
Astrophysical hints

Excess of electrons/positrons in the cosmic rays, first seen by Pamela, confirmed by Fermi & AMS-02.



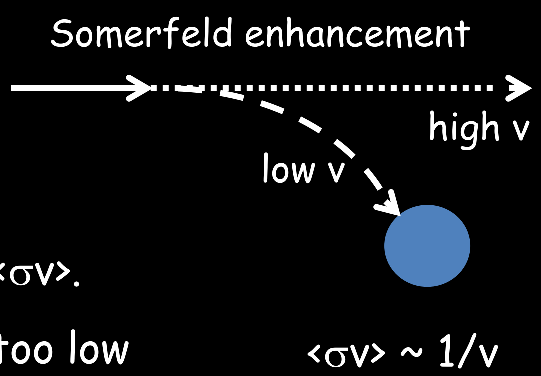


No comparable enhancement of antiprotons!



Wimp-like TeV-scale dark matter particles annihilate into light dark photons (10 MeV – few GeV range), which subsequently decay to electrons/positrons (Arkani-Hamed et al., Pospelov & Ritz):

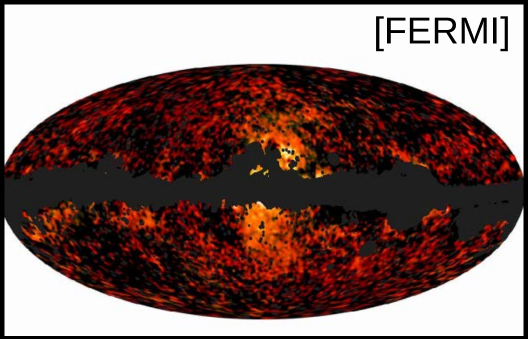
- Large branching fraction to leptons
- Protons kinematically suppressed
- Hard energy spectrum
- Correct relic abundance with Somerfeld enhancement



  - Relic abundance depends on annihilation rate $\Omega_{DM} \sim 1/\langle\sigma v\rangle$.
  - Annihilation rate derived from cosmic flux gives Ω_{DM} too low by a factor 100-1000 (“boost” factors invoked to solve this problem for many models).
  - Cross-section is enhanced at low velocities for light A’, boosting Ω_{DM} to observed values.

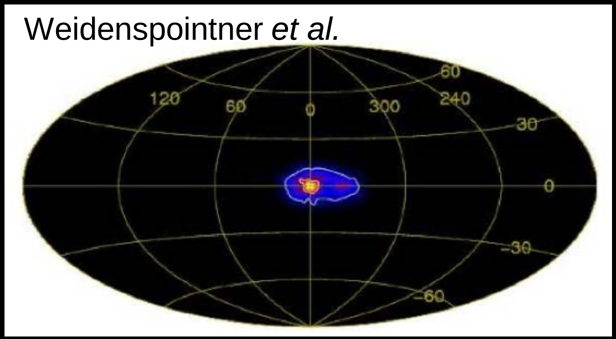
Such a model could also explain several other anomalies

WMAP / Fermi haze



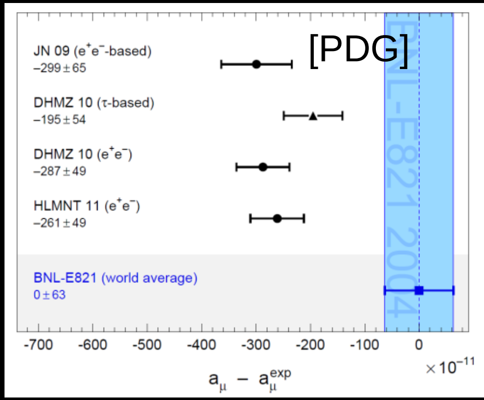
[Finkbeiner Dobler et al.,]

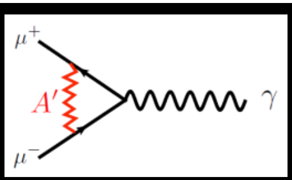
Integral 511 keV line



[Finkbeiner & Weiner]

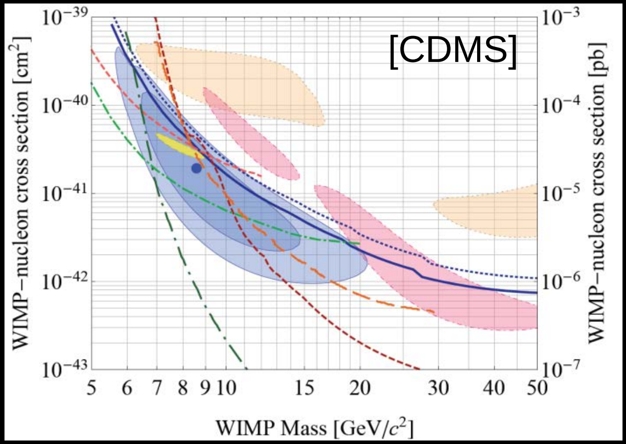
Anomalous muon g-2



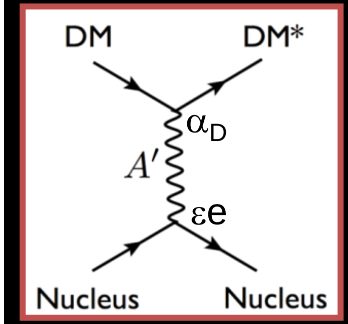


[Pospelov]

Direct detection anomalies



CDMS, arXiv:1304.4279



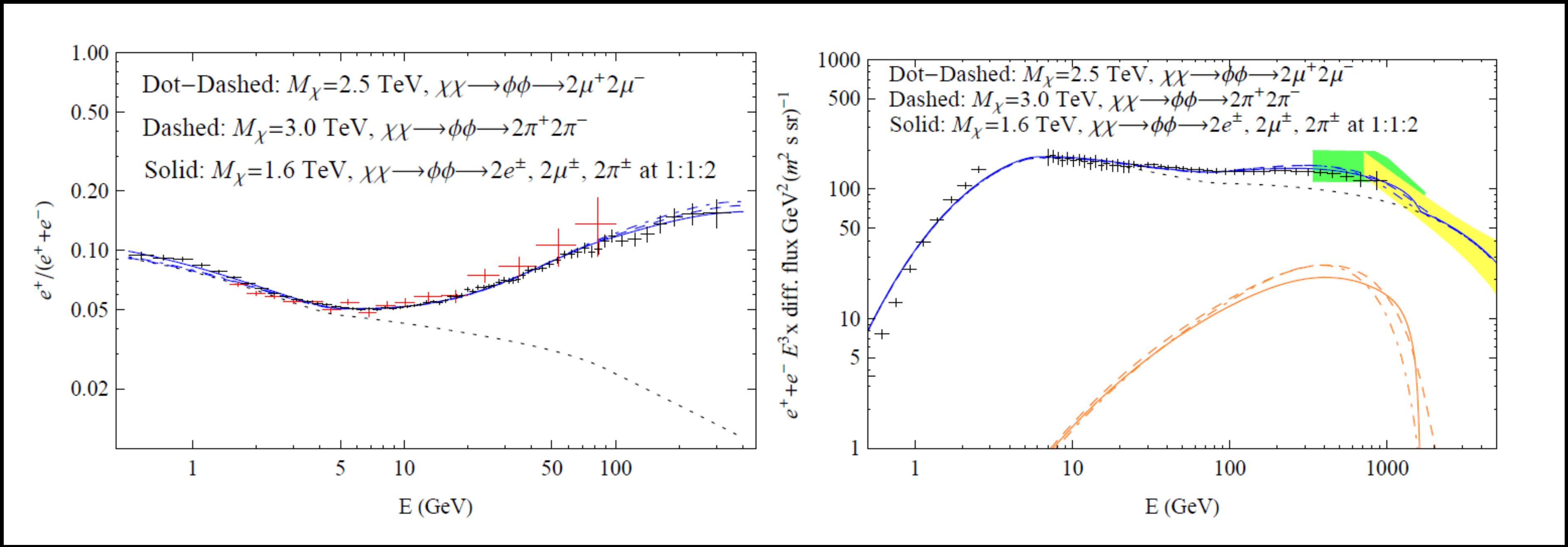
[Slatyer, Schuster&Toro,...]

And several others....

Would require another seminar to discuss them all...

Latest astrophysical fits

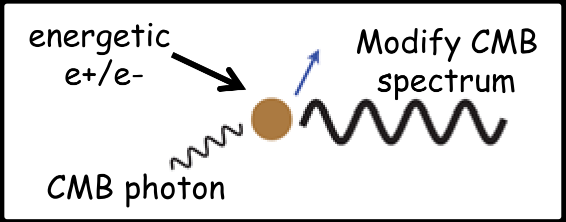
Cholis & Hooper , arXiv:1304.1840

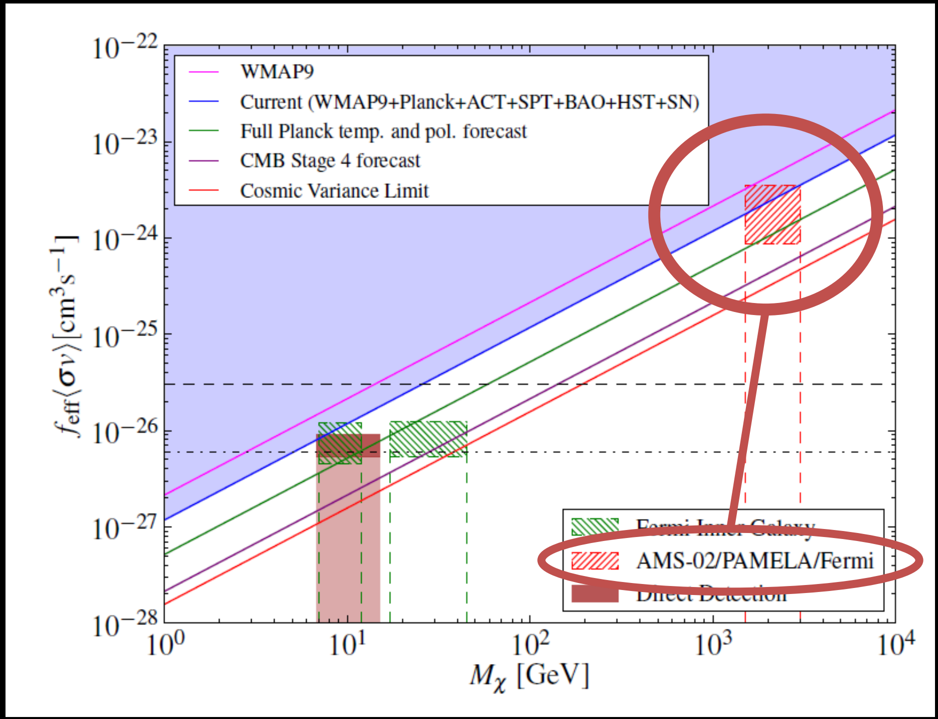


Fits to the cosmic ray spectra prefer few TeV dark matter particles and A' mass above the muon decay threshold, but there are still many uncertainties!

If DM annihilation into light dark photons is the source of e-/e+ excess, other astrophysical phenomena should be observable (e.g. diffuse gamma ray emission, CMB).

In particular, primordial DM annihilation injects energy in the CMB → distorts spectrum





Madhavacheril, Sehgal and Slatyer, arXiv:1310.3815

CMB spectrum

- Powerful constraints, start probing dark photon models
- Planck polarization data and additional AMS-02 data may provide an answer
- Model uncertainties are not negligible and could weaken constraints!

This is actively debated !!!

At this point…

New theory of dark matter based on dark sector(s)

- Light new mediator (dark photon A') with a MeV – GeV mass
- Mixing between dark sector – SM with $\varepsilon \sim 10^{-5} - 10^{-3}$ (could be smaller)
- Could have a rich structure

Anomalies from astrophysical data, direct detection and precision measurements

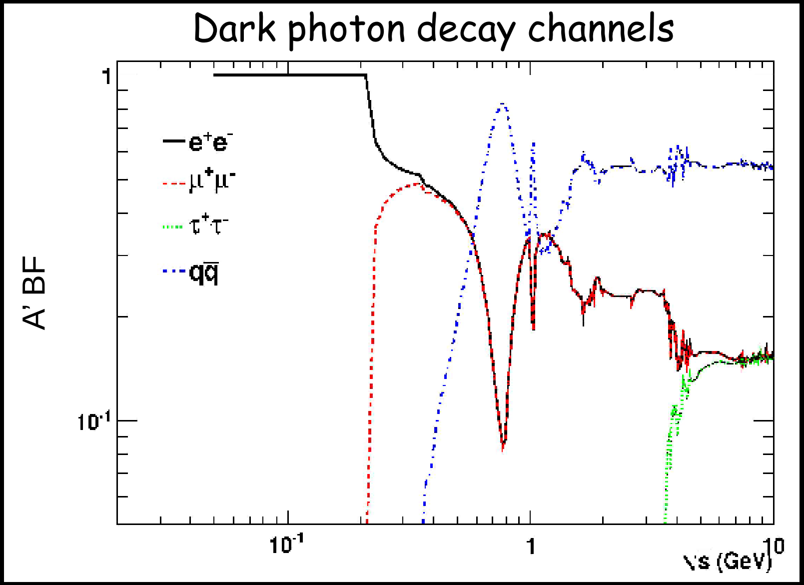
- Could be explained by dark sector
- Could have another origin, be statistical fluctuations or instrumental effects
- Dark matter could be composite with a dark sector sub-component
- …

But it made us realize the amazing possibilities at the GeV-scale, and the possibilities to probe them in laboratory at low energy!

Probing dark sectors at low-energy colliders

Particle physics experiments

- Can produce dark photons. In fact, photons in any process can be replaced by a dark photon (with an extra factor of ε).
- Decays back to lepton/quark pairs → search for resonances



Lepton contribution dominates at low masses, and is still ~30% at high masses!
(binning too large to show narrow resonances)

Particle physics implications

Particle physics experiments

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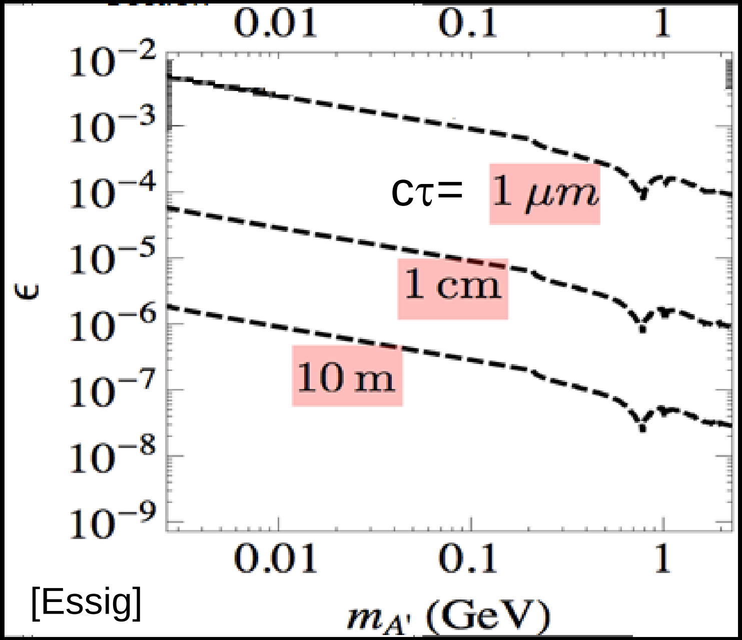
- Dark photon width is small (~ εe) and could be long-lived → displaced decay vertex



Particle physics implications

Particle physics experiments

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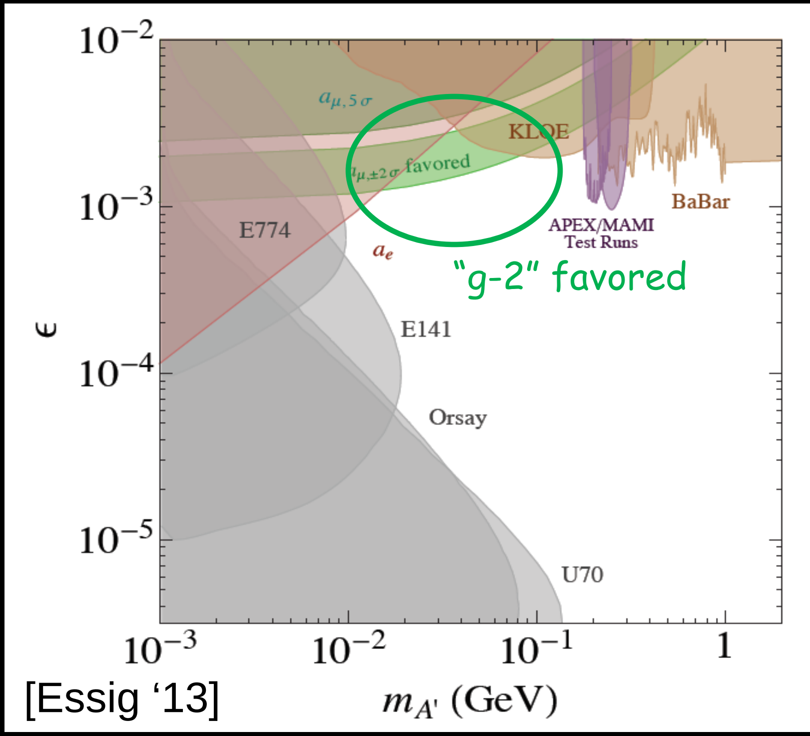
- Decays back to lepton/quark pairs → search for resonances
- Dark photon width is small (~ εe) and could be long-lived → displaced decay vertex
- Current bounds on the mixing para-meter ε are shown as a function of the dark photon mass.
- Constraints from electron/muon g-2, beam dump and fixed target experiments and e^+e^- colliders (some constraints reinter-preted from limits of other measurements by theorists, e.g. BABAR)

Constraints on ε vs. $m_{A'}$

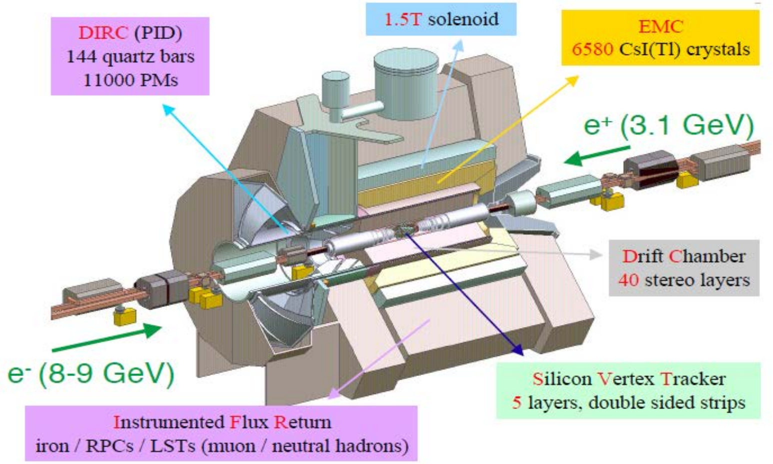


Pospelov;
Bjorken, Essig, Schuster, Toro
Andreas, Niebuhr, Ringwald
Batell, Pospelov, Ritz;
Essig, Harnik, Kaplan, Toro
Blumlein, Brunner;
Dent, Ferrer, Krauss
Essig Schuster, Toro, Wojtsekhowski
KLOE, APEX, MAMI/A1 Collab.
Davoudiasl, Lee, Marciano;
Endo, Hamaguchi, Mishima

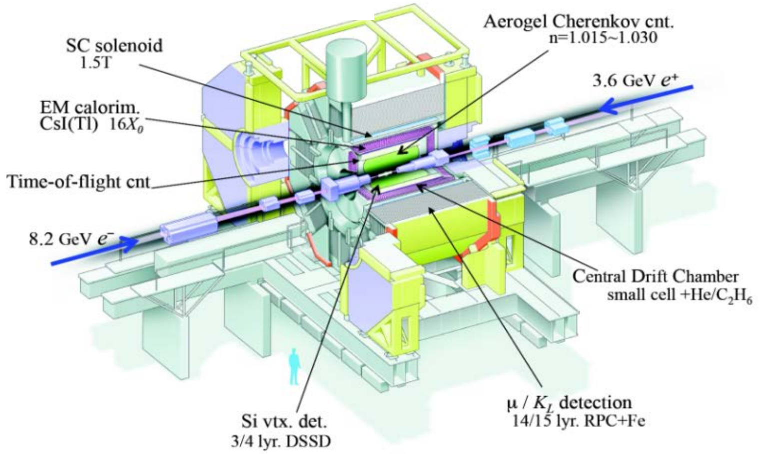
Low-energy high-luminosity e^+e^- colliders offer a low-background environment to search for MeV/GeV-scale hidden sector (in particular high masses) and probe their structure

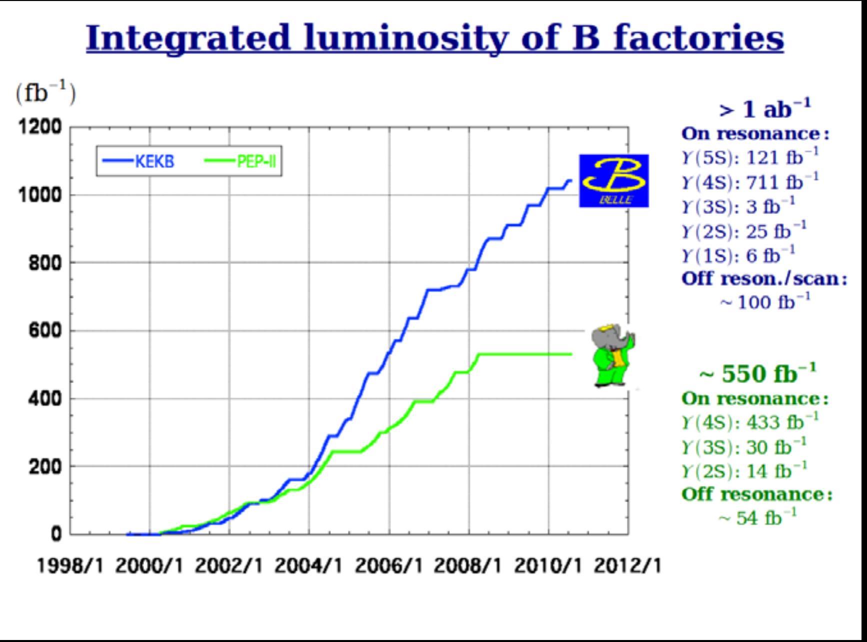
***BABAR* / Belle collected around 500/1000 fb^{-1} of data around the Υ(4S) resonance**

BABAR detector

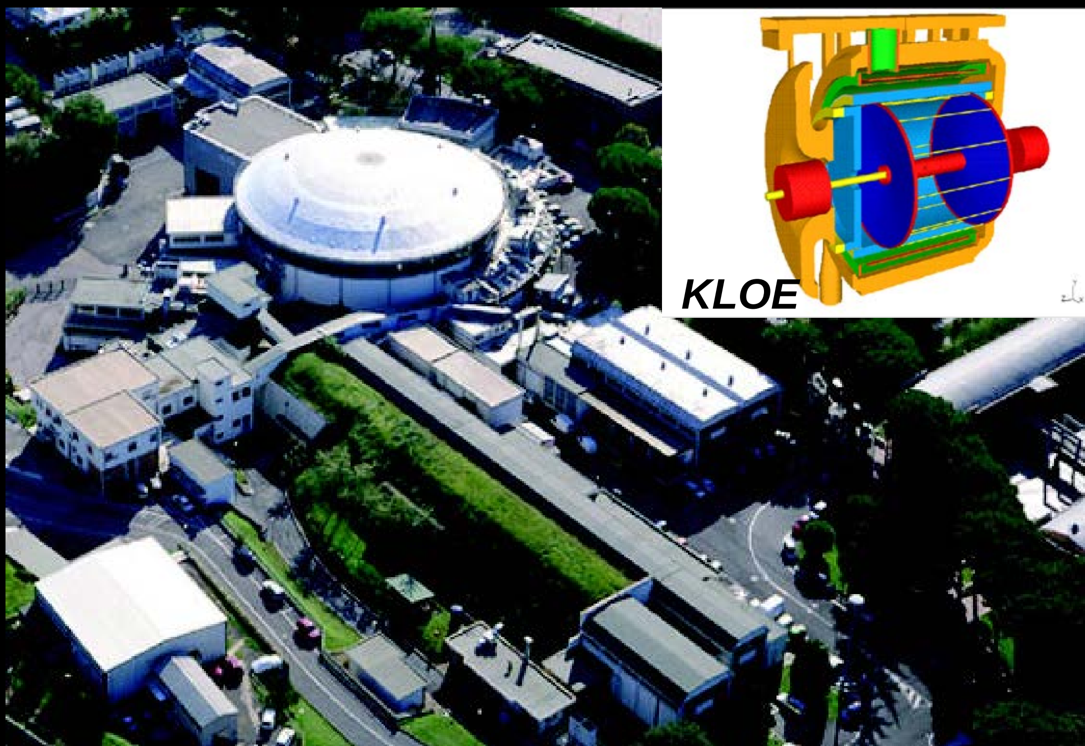


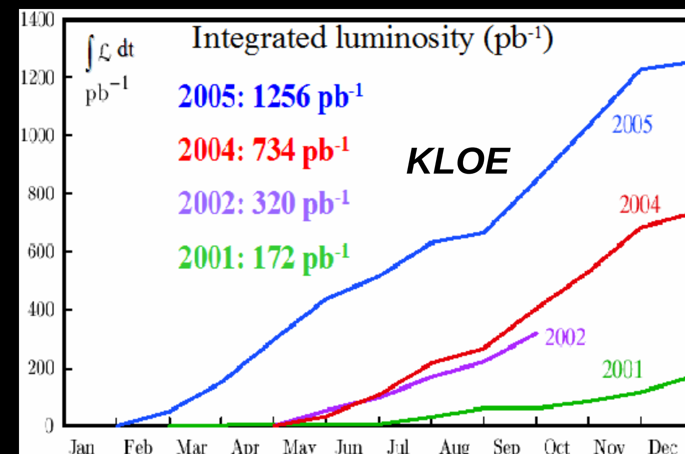
Belle detector





KLOE collected around 2.5 fb^{-1} of data around the ϕ resonance





Cross-section for dark photon production σ~1/s, partially compensating the lower luminosity (still an advantage for B-factories)

Possible dark sector searches at e^+e^- colliders

Search for dark photon

$e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

$e^+e^- \to \gamma A'$, $A' \to$ invisible

Search for dark photon in meson decays

$\pi^0 \to \gamma\, l^+l^-$, $\eta \to \gamma\, l^+l^-$, $\phi \to \eta\, l^+l^-$,...

Search for dark Higgs boson

$e^+e^- \to h'A'$, $h' \to A'A'$

$e^+e^- \to h'A'$, $h' \to$ invisible

Search for dark boson(s)

$e^+e^- \to A'^* \to W'W'$.

$e^+e^- \to \gamma A' \to W'W''$

Search for dark hadrons

$e^+e^- \to \pi_D + X$, $\pi_D \to e^+e^-, \mu^+\mu^-$

Search for dark scalar (s) and dark pseudoscalar (a)

$B \to K^{(*)}s \to K^{(*)}\, l^+l^-$

$B \to K^{(*)}a \to K^{(*)}\, l^+l^-$

$B \to ss \to 2(l^+l^-)$

$B \to K\, 2(l^+l^-)$

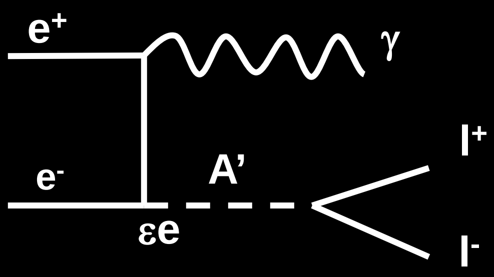
$B \to 4(l^+l^-)$

Disclaimer

"Some of the results shown here have not yet been approved by the BABAR experiment. They represent my own work and I have been approved to show them as such."

A dark photon can be produced in

$e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$

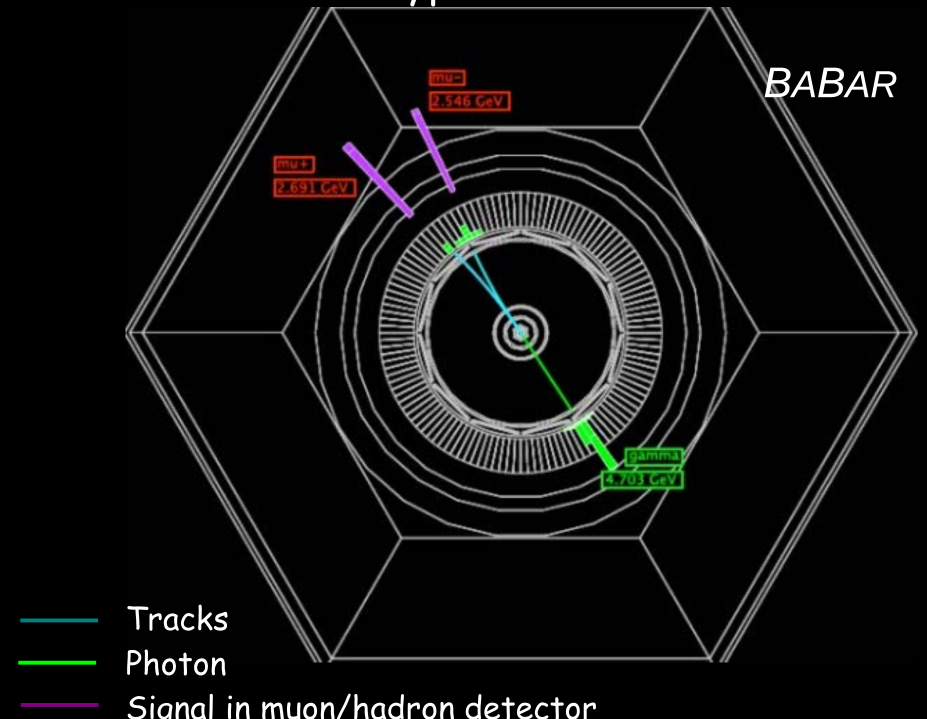


On-going analysis at BABAR, **the following results are not approved yet !**

Event selection

- 2 tracks + 1 photon
- Constrained fit to the beam energy and beam spot
- Particle identification (e/mu)
- Kinematic cuts to improve purity
- Quality cuts on tracks and photons

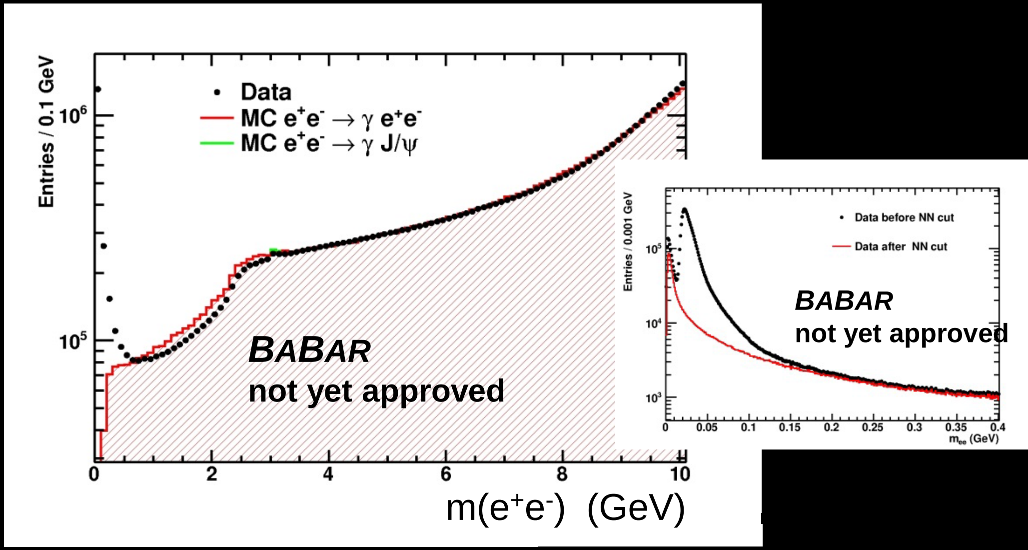
Typical event



Direct dark photon production

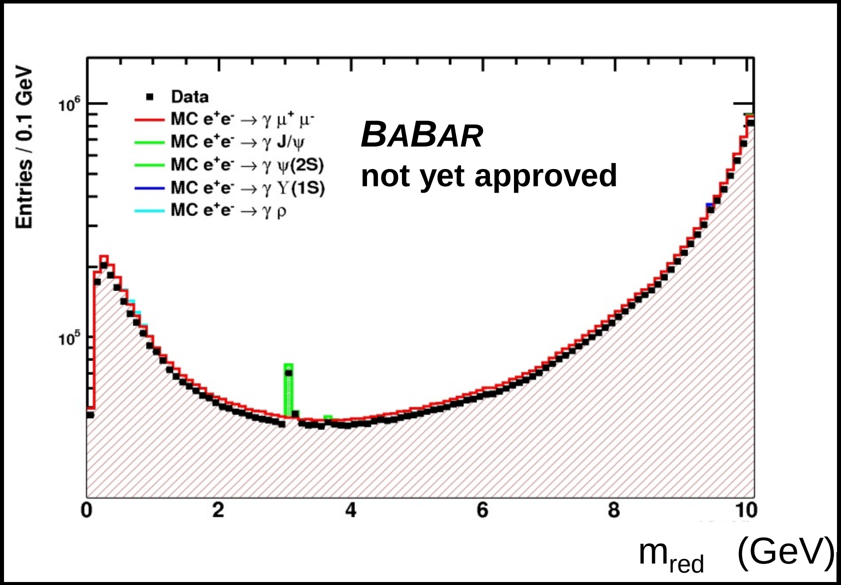
Di-electron mass spectrum

- Globally well reproduced by MC above 1 GeV (higher-order QED contributions at low masses)
- Background from photon conversions suppressed by neural network



Di-muon mass spectrum

- Plot the reduced mass (smoother near threshold): $m_{red} = (m_{\mu\mu}^2 - 4\, m_\mu^2)^{1/2}$
- Globally well reproduced by MC, correct for differences in efficiencies

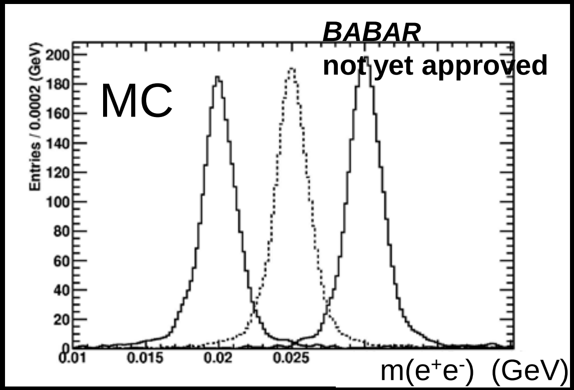


Good data-MC agreement at the J/ψ, Ψ(2S), Υ(1S) resonances

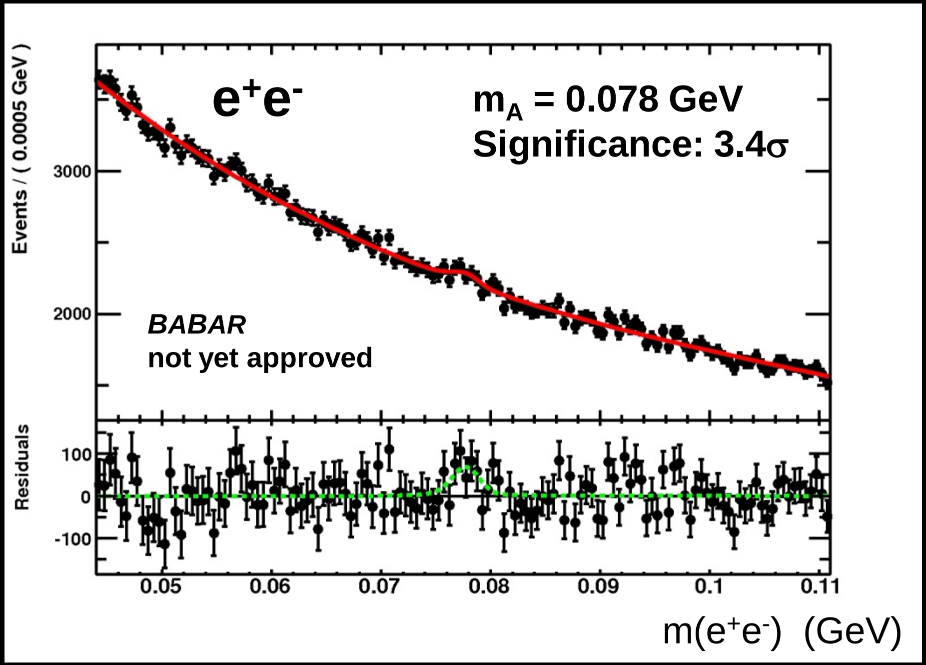
Direct dark photon production

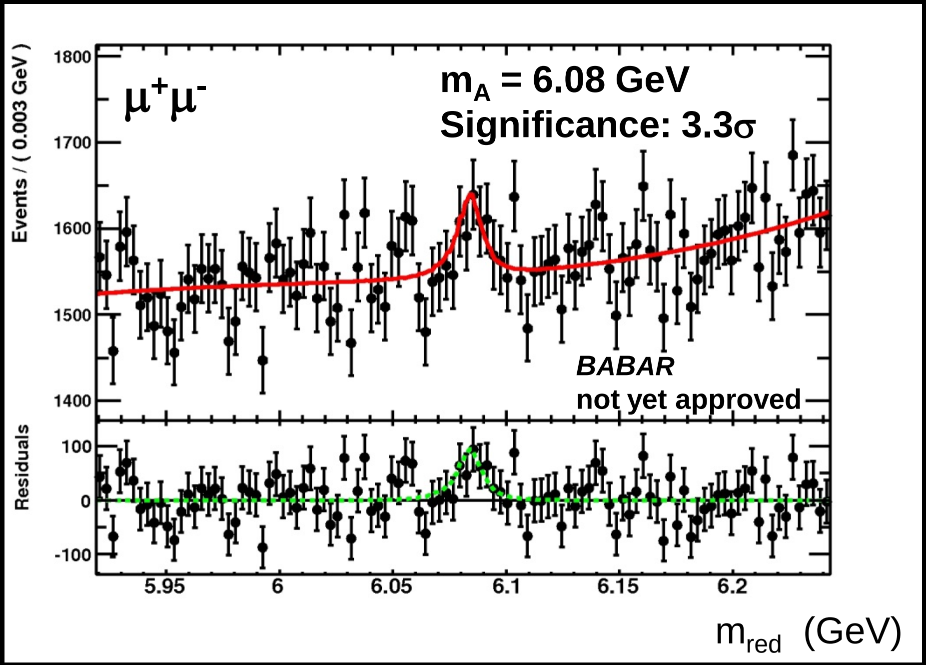
Extract signal by a series of maximum likelihood fits to the data over sliding mass intervals centered around the A′ mass.

Signal modeled using mass histograms from MC, interpolated between known points (cdf interpolation). Background modeled as 3rd order Chebychev polynomials.



Example of fits to the data (Υ(4S) sample)

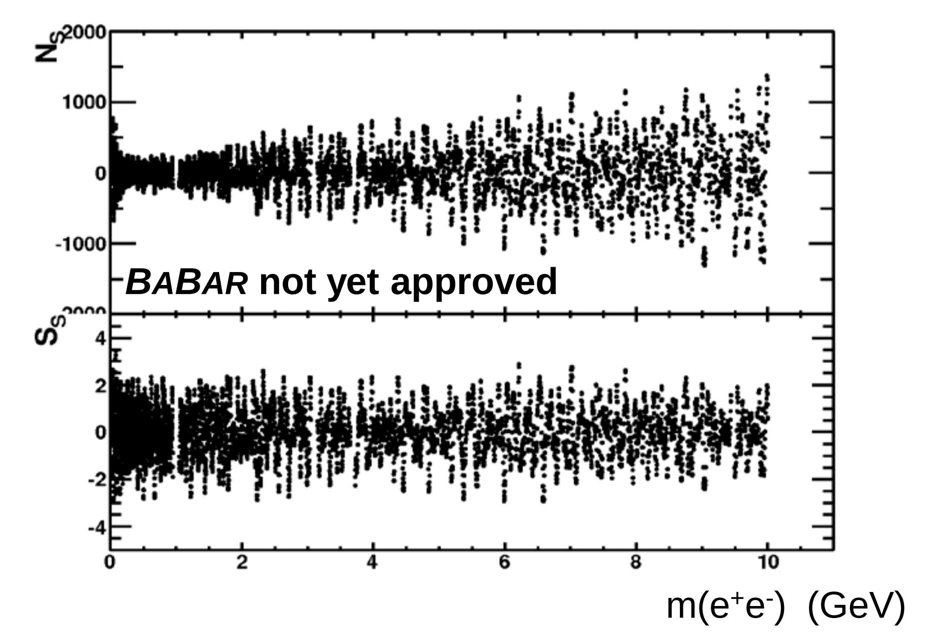




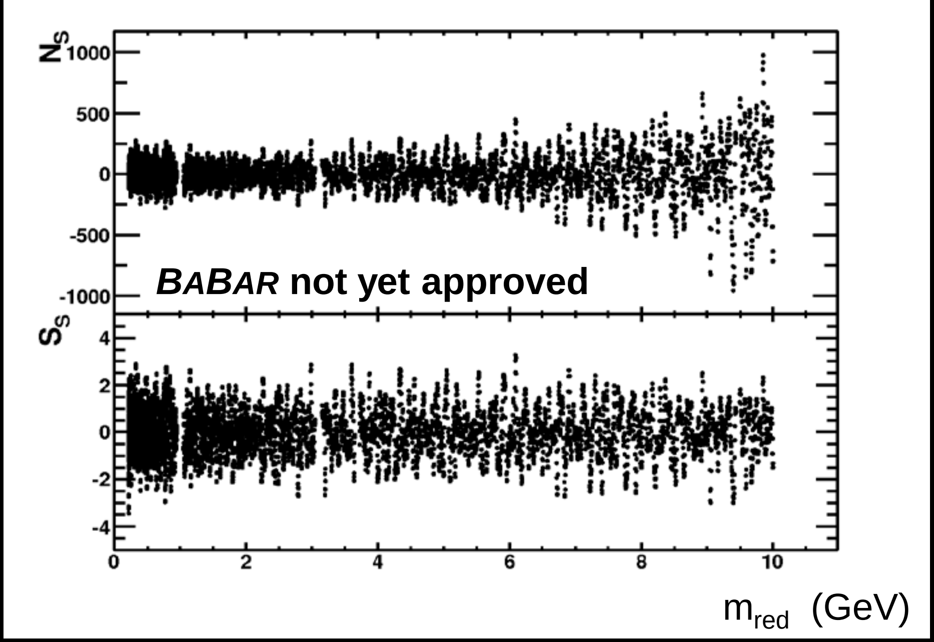
Direct dark photon production

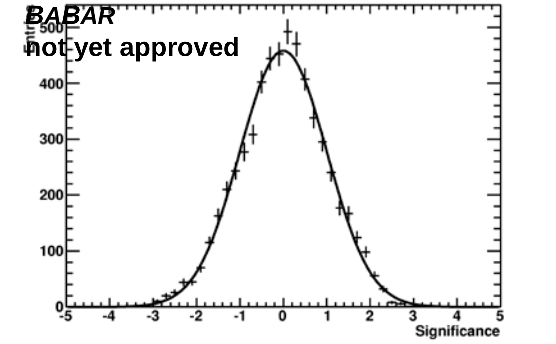
Distribution of signal events (N_s) and signal significance(S_s) from the fit as a function of the dark photon mass ($m_{A'}$) on the Υ(4S) data. Scan step = half A' mass resolution

$A' \rightarrow e^+e^-$



$A' \rightarrow \mu^+\mu^-$



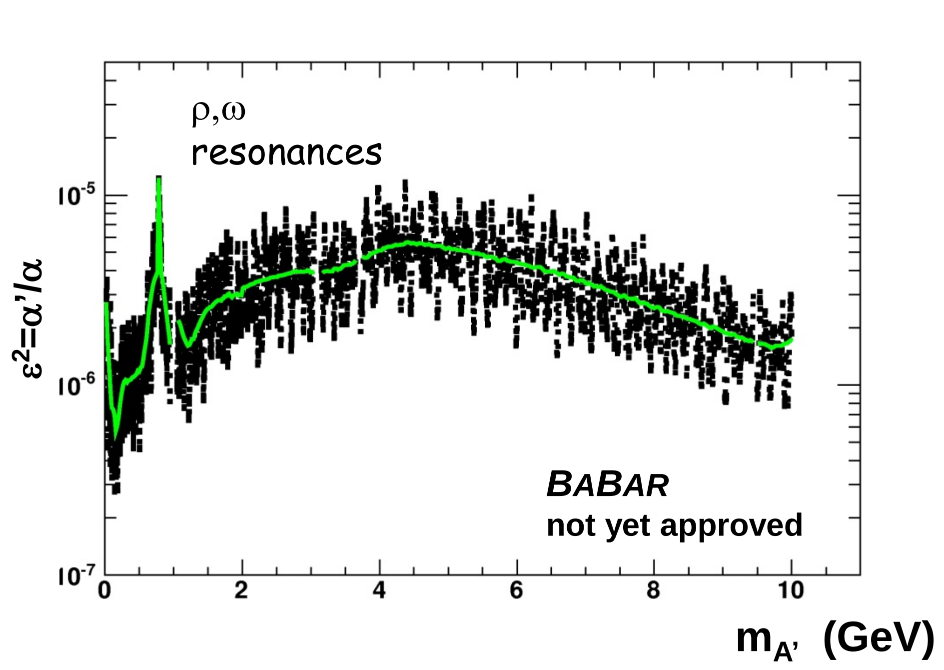


No significant excess observed ☹

Direct dark photon production

90% CL upper limits on the mixing parameter $\varepsilon^2 = \alpha'/\alpha$ (Y(4S) data)

$A' \rightarrow e^+e^-$



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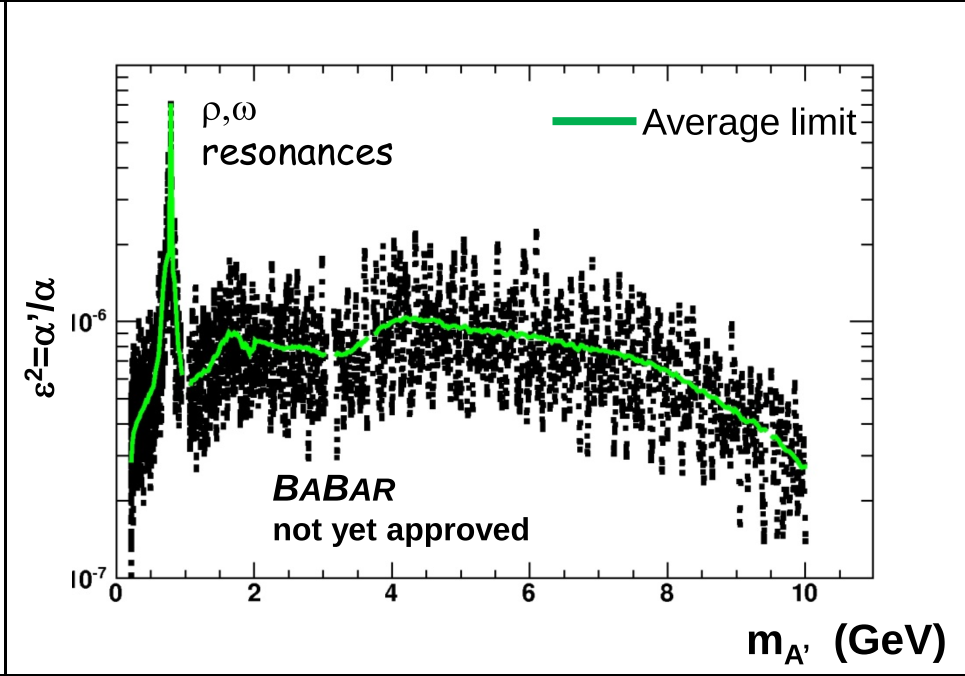

Average limit to guide the eye

Limits at the level of 10^{-6} – 10^{-5}.
Another 10% of data is being analyzed and should slightly improve the limits.

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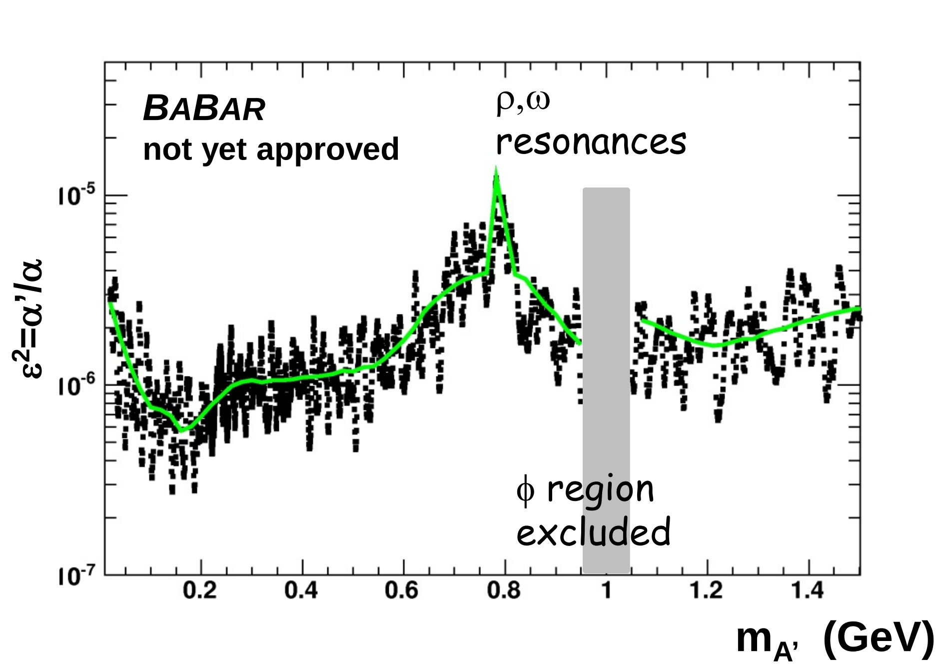
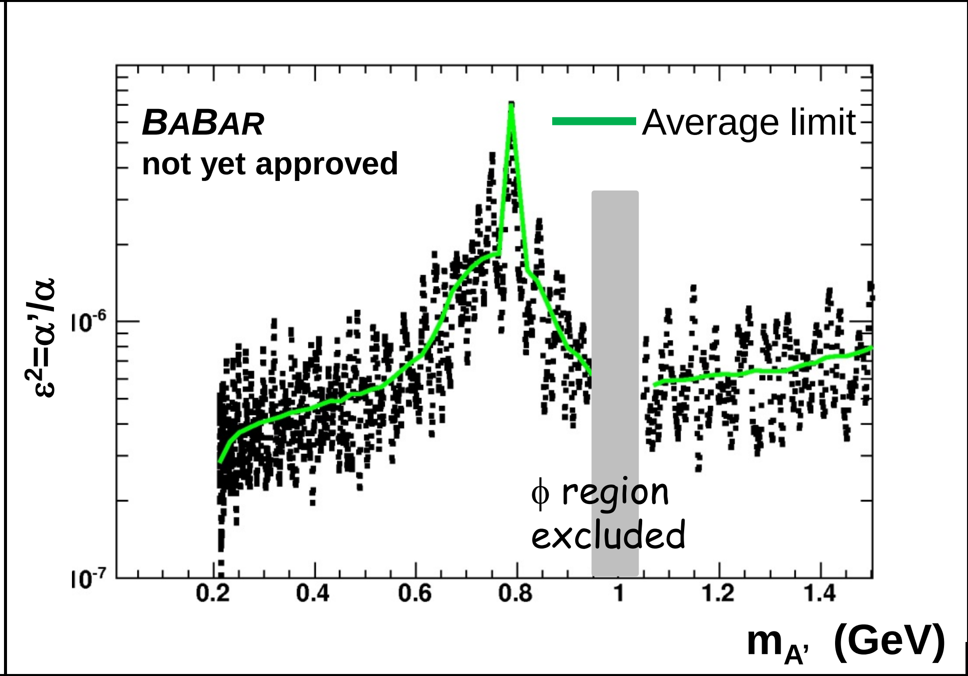


$A' \rightarrow \mu^+\mu^-$



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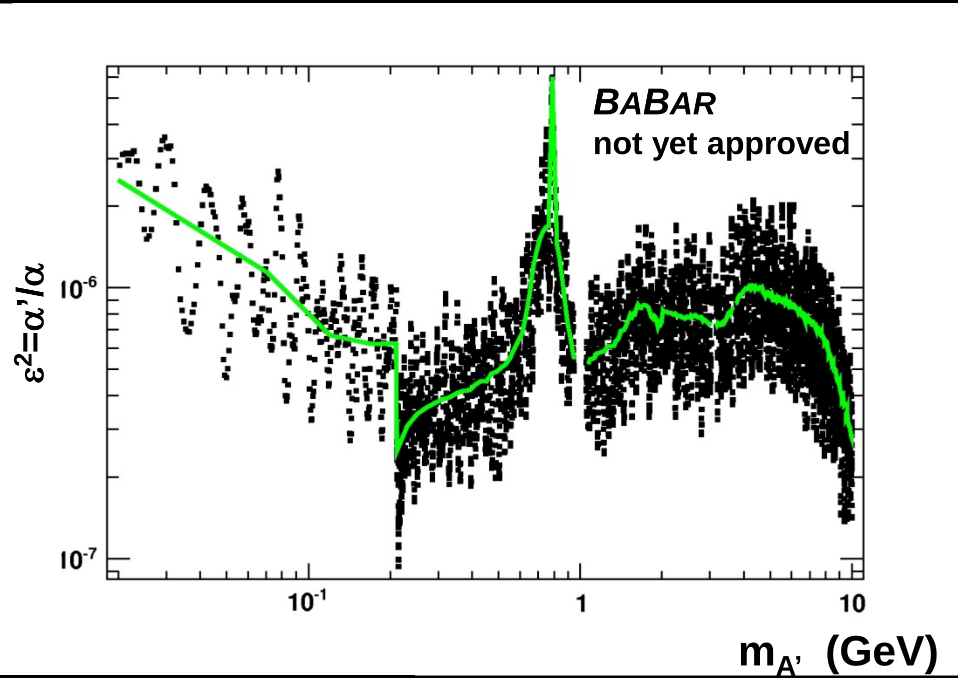
Limits at the level of 10^{-6} – 10^{-5}.
Another 10% of data is being analyzed and should slightly improve the limits.

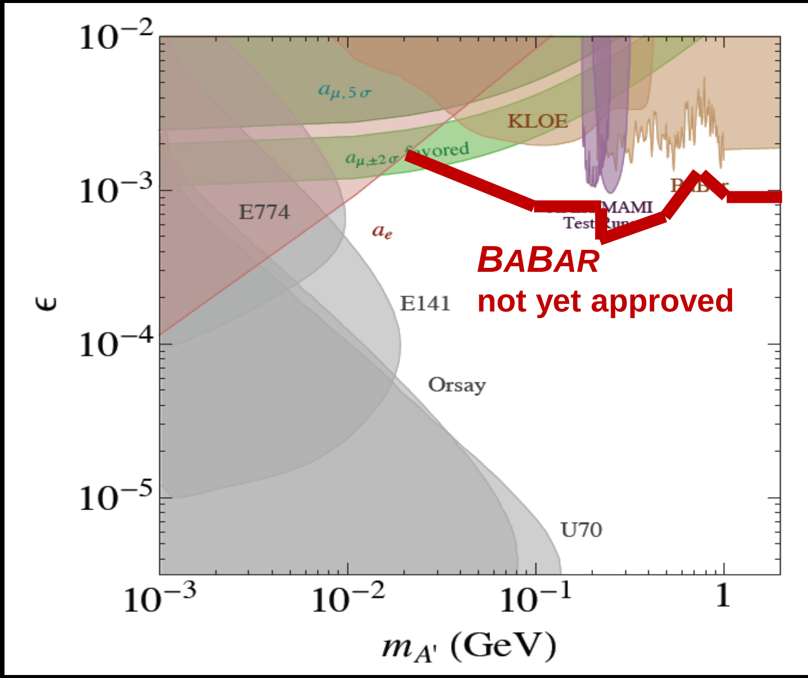
Direct dark photon production

Combined e^+e^- / $\mu^+\mu^-$ limit



Average limit to guide the eye

Comparison with current bounds

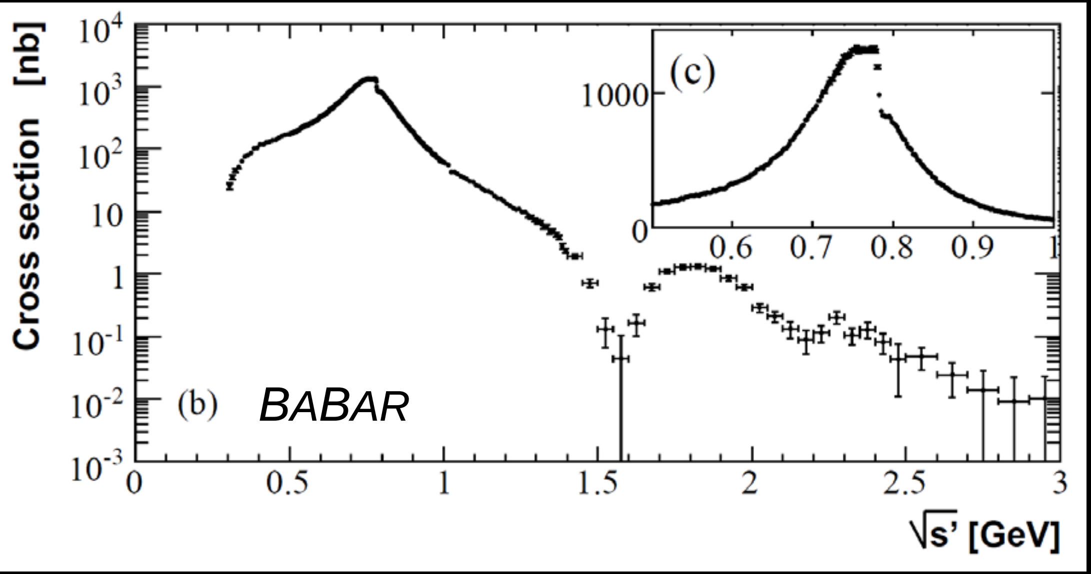


Should probe almost all "g-2" preferred region and improve bounds down to $\sim 10^{-3}$ from 20 MeV to 10 GeV.

The dipion final state: **$e^+e^- \rightarrow \gamma A'$, $A' \rightarrow \pi^+\pi^-$**

BABAR measured the $e^+e^- \rightarrow \gamma \pi^+\pi^-$ cross-section with ~1/2 of its data (important input for the calculation of HVP contributions to g-2), but no limits on the dark photon production have been extracted so far.

$e^+e^- \rightarrow \gamma \pi^+\pi^-$ cross-section



PRL 103 (2009) 231801

No large contribution of a narrow resonance is seen.

Could potentially improve limits on ε^2 in the ρ-meson region.

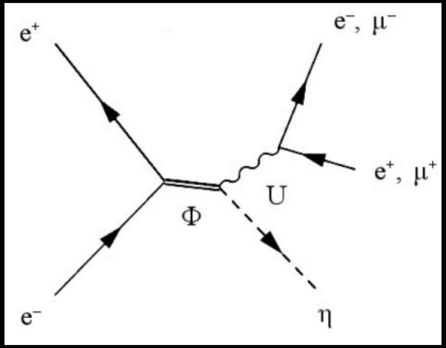
Dark photon production in meson decays

PLB 706 (2012) 251
PLB 720 (2013) 111

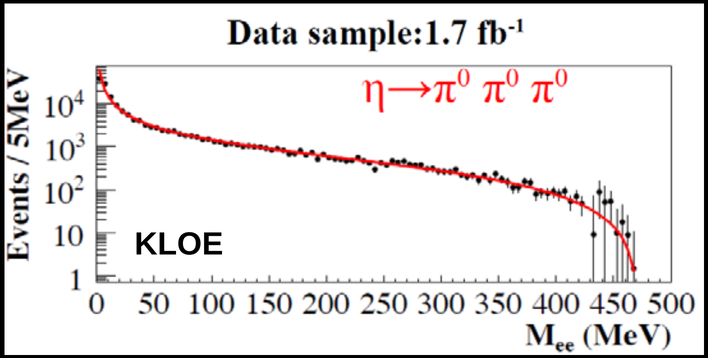
KLOE search for A' in ϕ decays with 1.5-1.7 fb^{-1} of data:
$\phi \to \eta A'$, $A' \to e^+e^-$

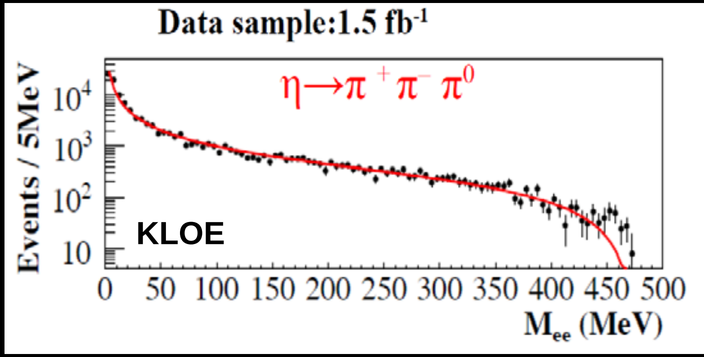
Limits on $\varepsilon^2 \sim$ few 10^{-6} - 10^{-5}

Also shown preliminary results for $e^+e^- \to \gamma\mu^+\mu^-$

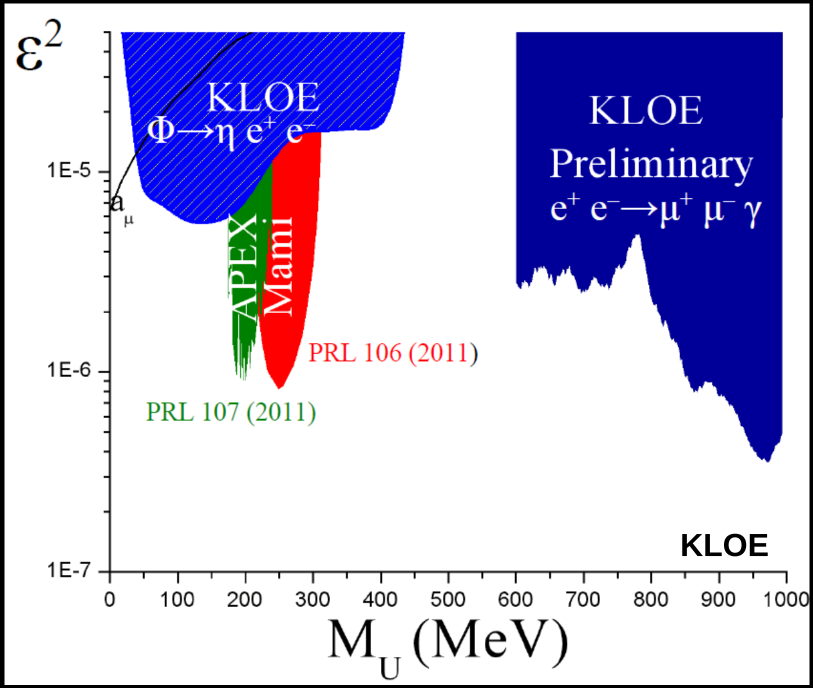


F. Curaciello





F. Curaciello



arxiv:0808.0017

Invisible dark sector

- Several scenarios where dark photons decay to invisible final states, e.g lighter dark sector particles (sub-GeV),…
- At e^+e^- colliders, we can search for

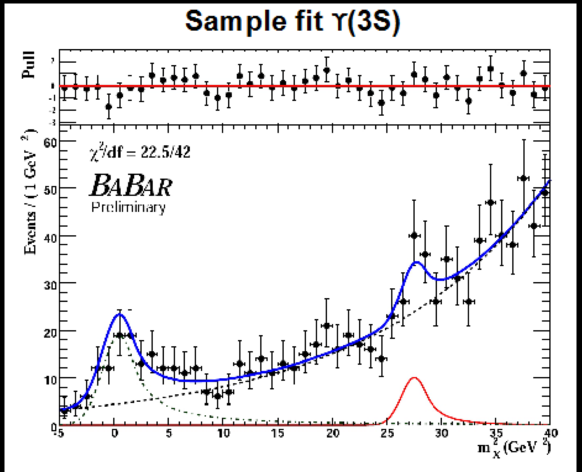
$$e^+e^- \rightarrow \gamma A' \;,\; A' \rightarrow \text{invisible}$$

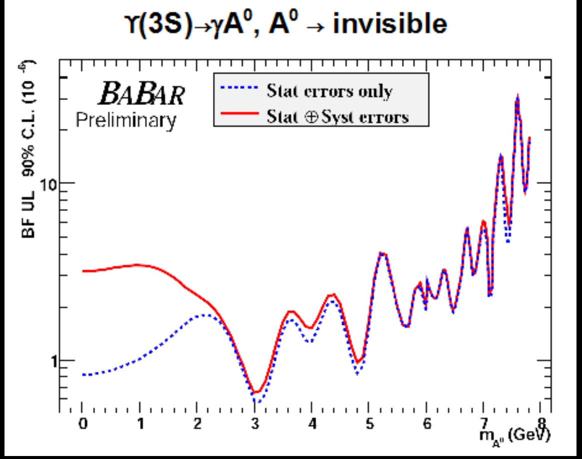
  by tagging the recoil photon in "single photon" events.
- Currently only a measurement of

  $\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

  at *BABAR* with A^0 a light CP-odd Higgs

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible,
new analysis in progress + extension to A'





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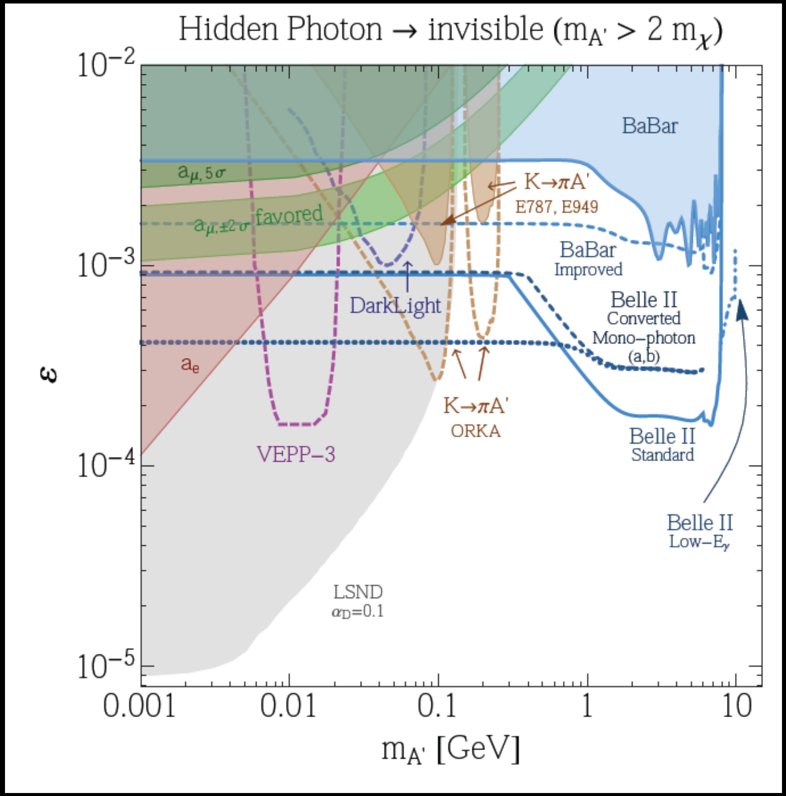
- Currently only a measurement of
  $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ invisible
  at *BABAR* with A^0 a light CP-odd Higgs
- Analysis extended to full dataset and the dark photon case, expect limits on ε at the level of 10^{-3}.
- Also constraints from (g-2)e, (g-2)μ, $K \to \pi\nu\nu$ decays

Essig *et al.*, arXiv:1309.5084



Major improvement possible with future experiments (e.g. Belle II)

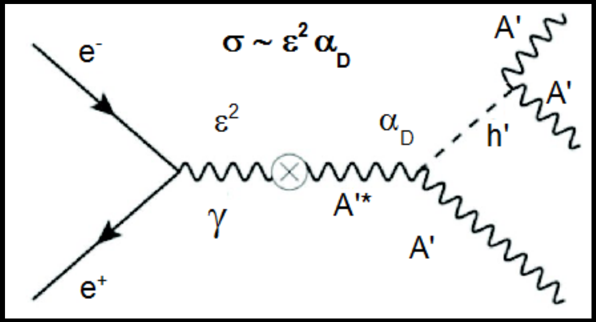
Dark Higgs boson

- Dark photon mass is generated via the Higgs mechanism, adding a dark Higgs boson (h')
- A minimal scenario has a single dark photon and a single dark Higgs boson.
- Theoretical prejudice for dark Higgs mass at the MeV-GeV scale.
- The Higgsstrahlung process

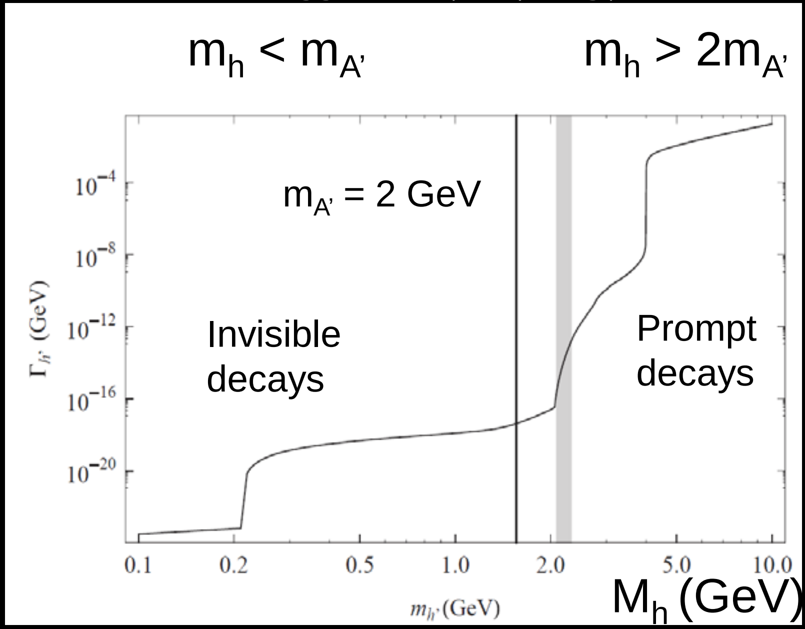
$$e^+e^- \rightarrow A'^* \rightarrow h' A'$$

is very interesting, as it is only suppressed by ε^2 and should have low background

- Also sensitive to the dark sector coupling constant $\alpha_D = g_D^2 / 4\pi$



Dark Higgs decay topology



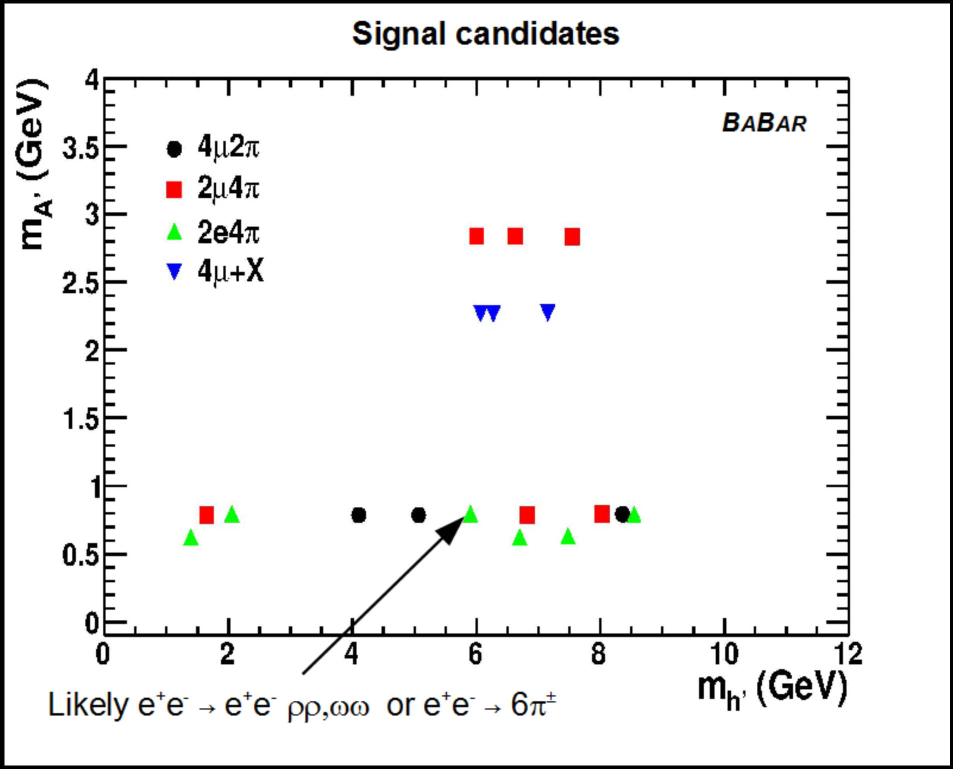
Search for prompt h' decays at BABAR:

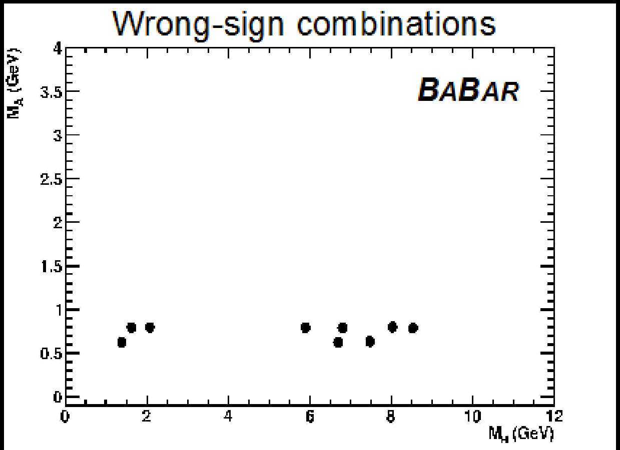
$$e^+e^- \rightarrow A'^* \rightarrow h' A',\ h' \rightarrow A' A'$$

Dark Higgs boson

PRL 108 (2012) 211801

- Six candidates are selected from the full *BABAR* dataset (~500 fb^{-1})
- Three entries for each event, corresponding to the three possible assignments of the $h' \to A'A'$ decay
- Estimate background from
  - wrong-sign combinations, e.g. $e^+e^- \to (e^+e^+)(e^-e^-)(\mu^+\mu^-)$
  - sidebands from final sample
  - rate for 6 leptons ~ 100x rate for $4\pi+2l$ above 1.5 GeV

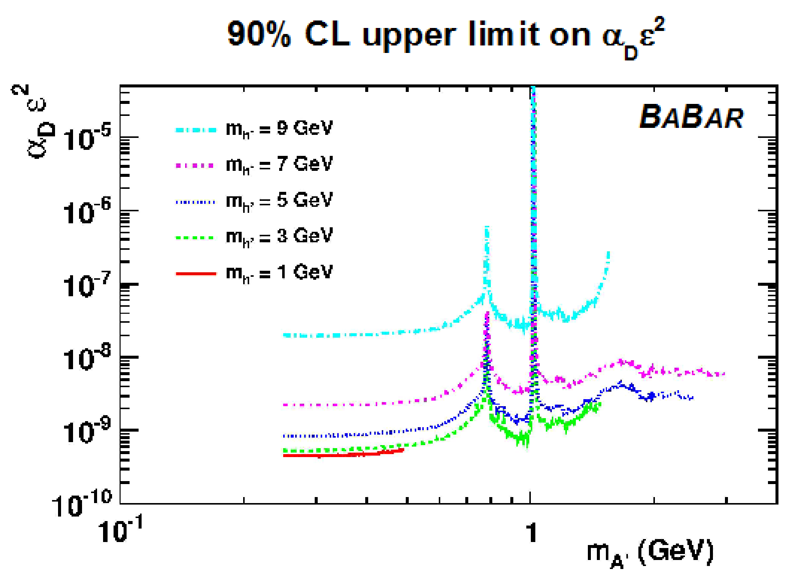


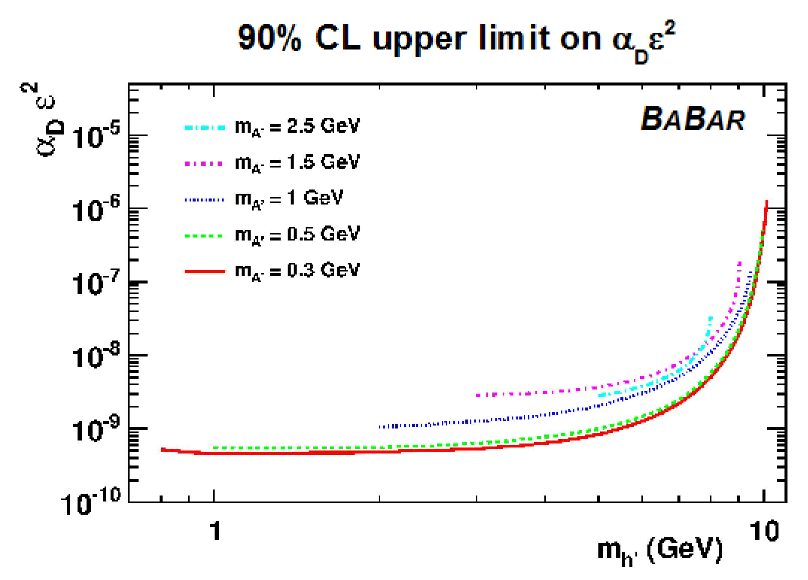


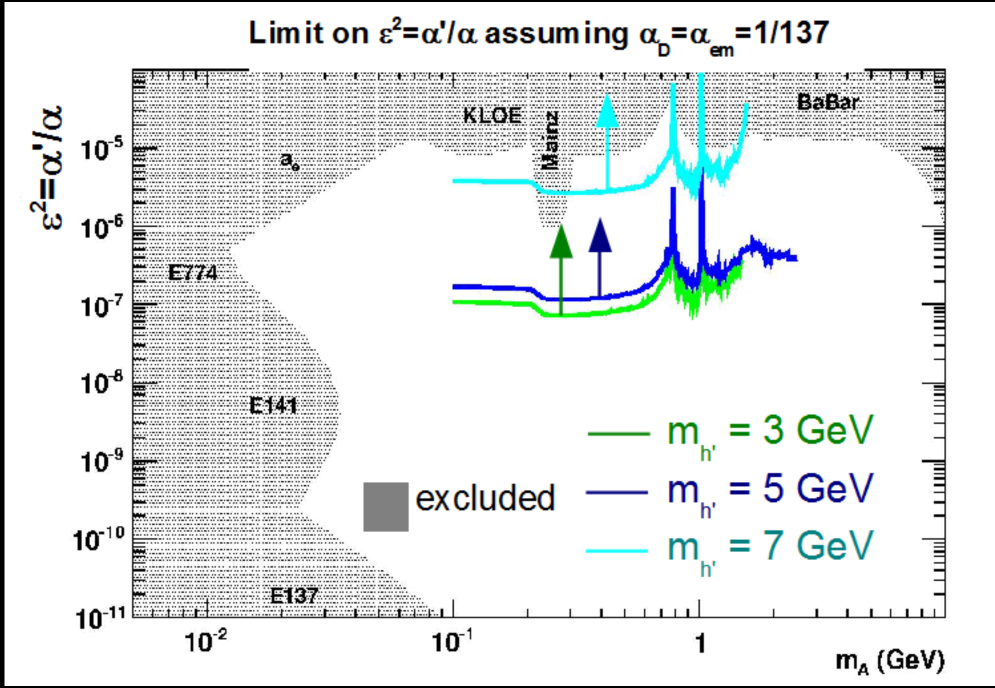
No events with 6 leptons, consistent with the pure background hypothesis

Dark Higgs boson

PRL 108 (2012) 211801





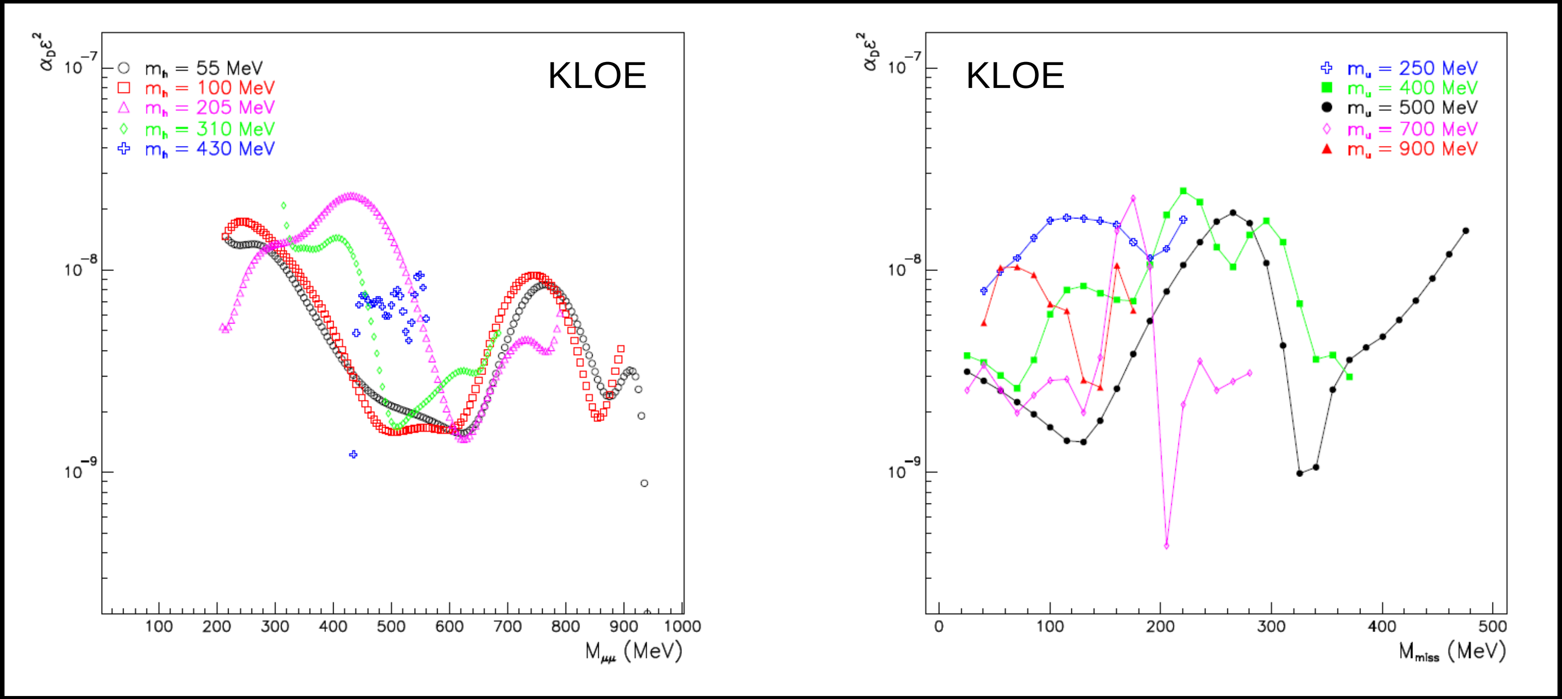


Substantial improvement over existing limits for $m_{h'} < 5 - 7$ GeV
(if a light dark Higgs boson exists, of course)

Frascati Phys.Ser. 56 (2012) 150-161

Invisible dark Higgs decay at KLOE

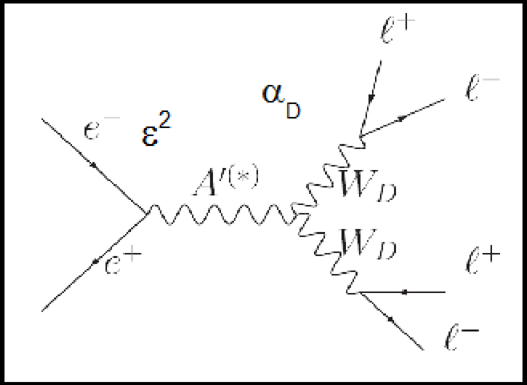
- Kinematic range $m_{h'} < m_{A'}$
- Signal: 2 leptons + missing energy
- Limits on $\alpha_D\varepsilon^2 \sim 10^{-9} - 10^{-8}$ for $2m_\mu < m_{A'} < 1000$ MeV and $m_{h'} < m_A$



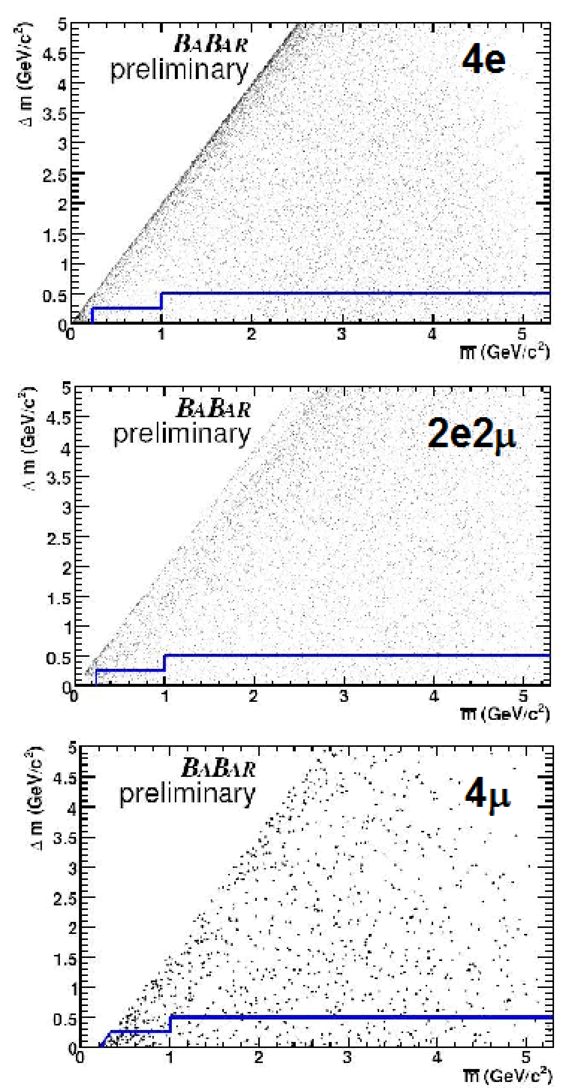
Non-abelian dark sector

arXiv:0908.2821

$e^+e^- \to A'^* \to W_D\, W_D'$,
$W_D^{(\prime)} \to e^+e^-, \mu^+\mu^-$



$\alpha_D = g_D^2 / 4\pi$
g_D dark sector gauge coupling

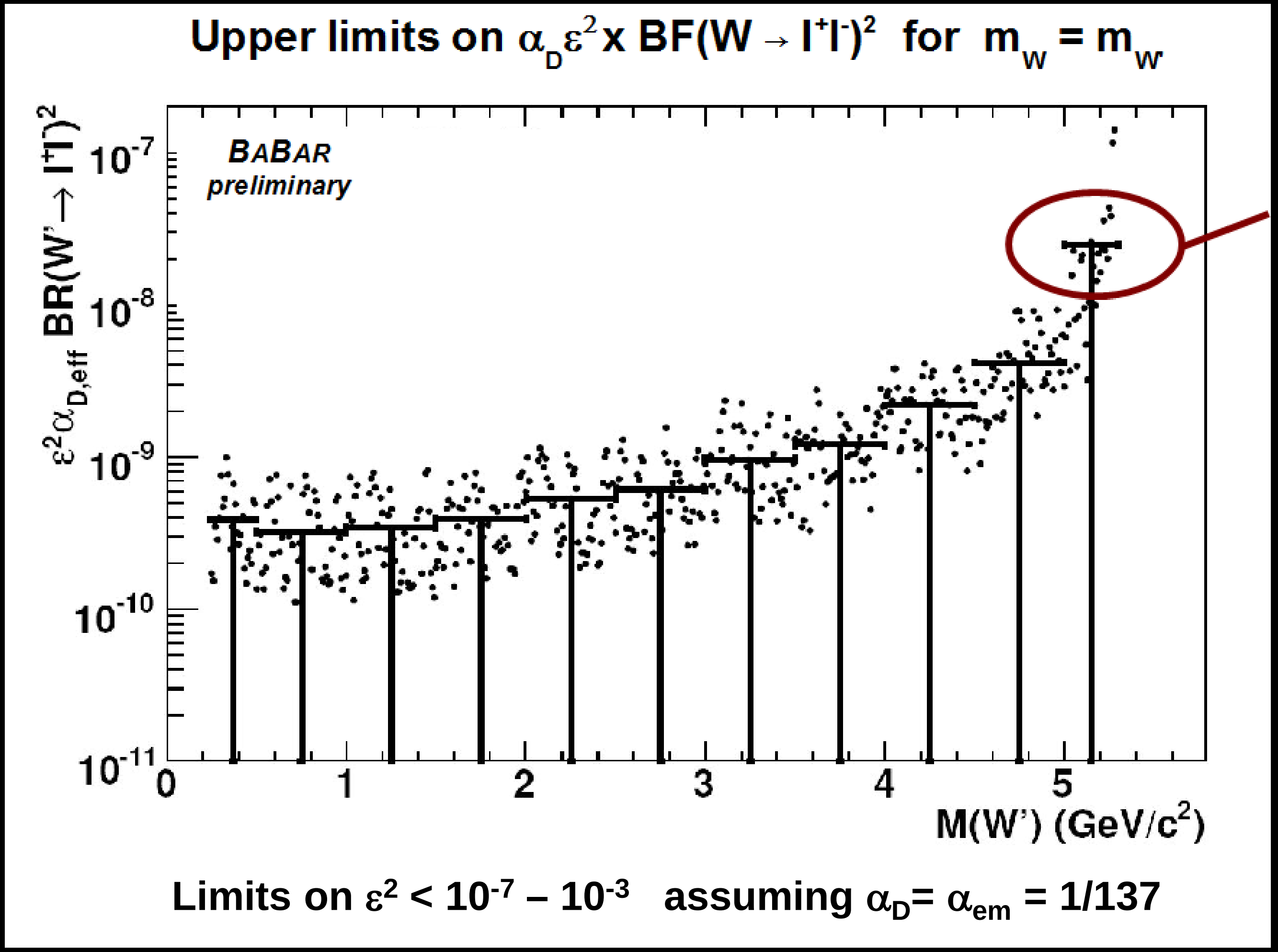


$\overline{m} = (m_{min} + m_{max})/2$
$\Delta m = (m_{max} - m_{min})/2$

- The simplest extension to a non-Abelian case is SU(2)xU(1), which has 4 bosons: A', W_D, W_D' and W_D''
- Can produce a pair of dark bosons though an off-shell A'.
- Search for two dileptonic resonances with similar mass

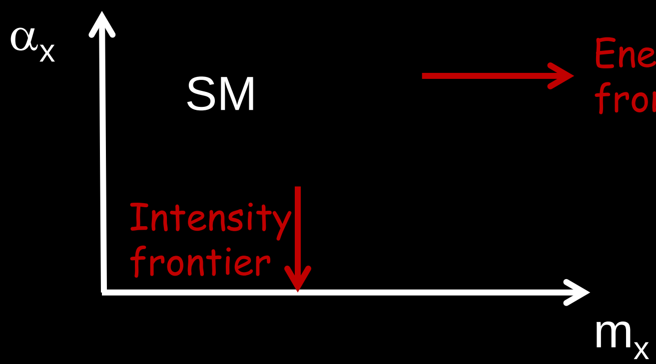
Non-abelian dark sector

arXiv:0908.2821



Expect similar limits for $m_W - m_{W'} >> 0$

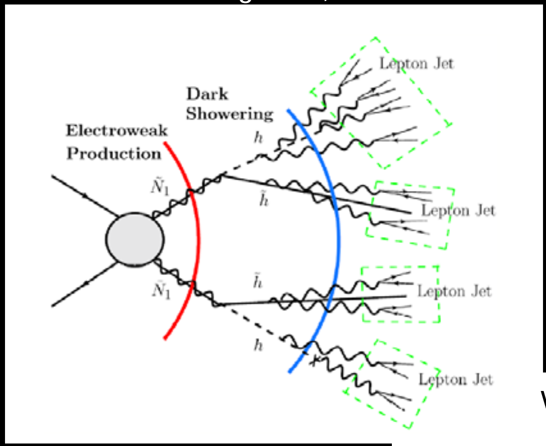
Direct production of dark photon suppressed at high energy



$$\text{Amplitude} \sim \frac{\alpha_X}{q^2 + m_X^2}$$

Difficult to probe $\alpha_X < 10^{-6}$ and $m_X \sim$ GeV at LHC
(hard ISR emission also suppressed)

Cheung et al., arXiv:0909.0290



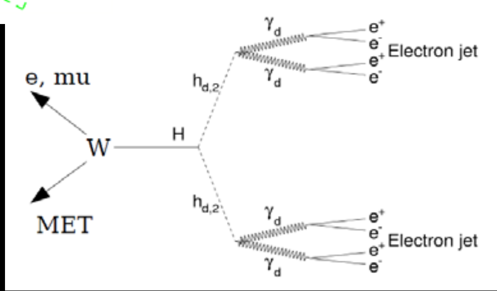
Instead, new particles (e.g SUSY) could decay into dark sector particles with a large BF.

In case of SUSY, bottom of cascade no longer stable, decays into dark photons → lepton jets.

Main characteriatics:

- Many leptons final state (e.g. lepton jets)
- Boosted dark sector particles → displaced vertices

W+H → e- jet [A. Haas]

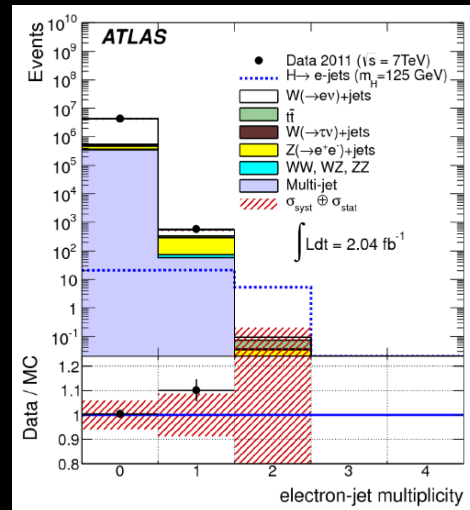


But New Physics needed in some models !!!

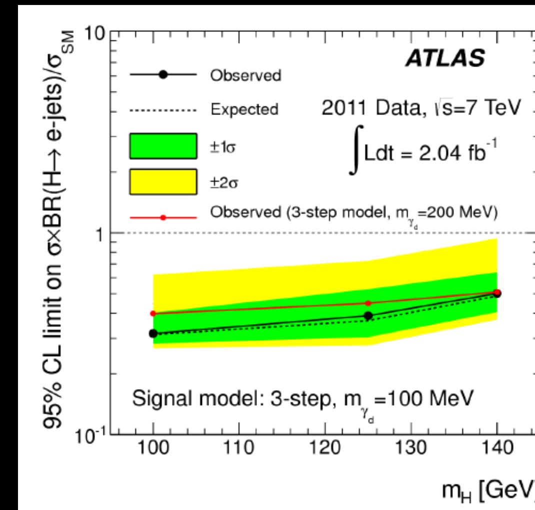
Dark sector searches at LHC

Search for
W+H → electron-jets + X

No excess of events with two electron jets observed

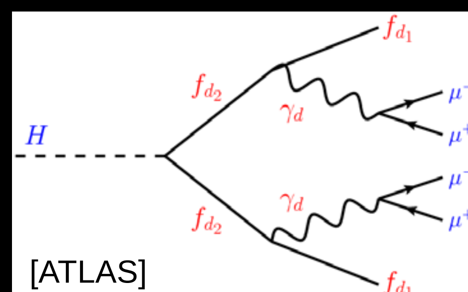


ATLAS Collab., New J.Phys. 15 (2013) 043009

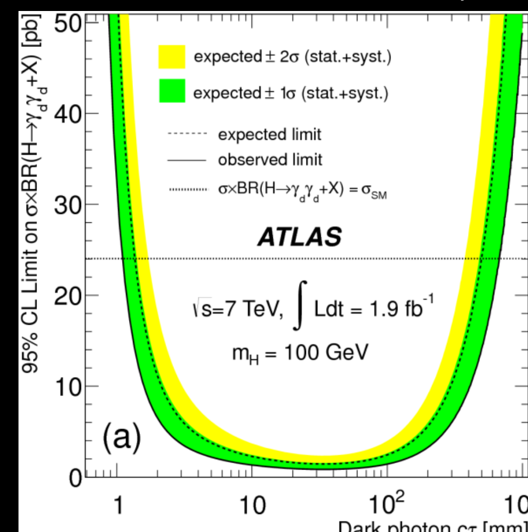


Search for
H → A' A' + X

No signal observed



Atlas Collab., PLB 721 (2013) 32

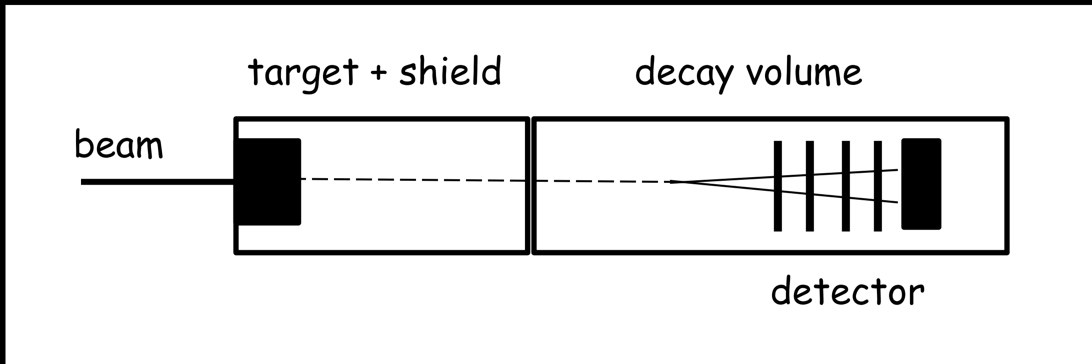


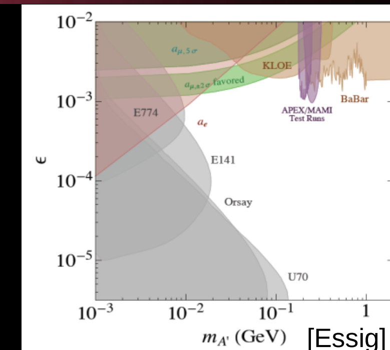
+ searches for SUSY lepton jets, H→muon jets
and possible searches for direct production, rare Z decays,..

Interesting program pursued at LHC

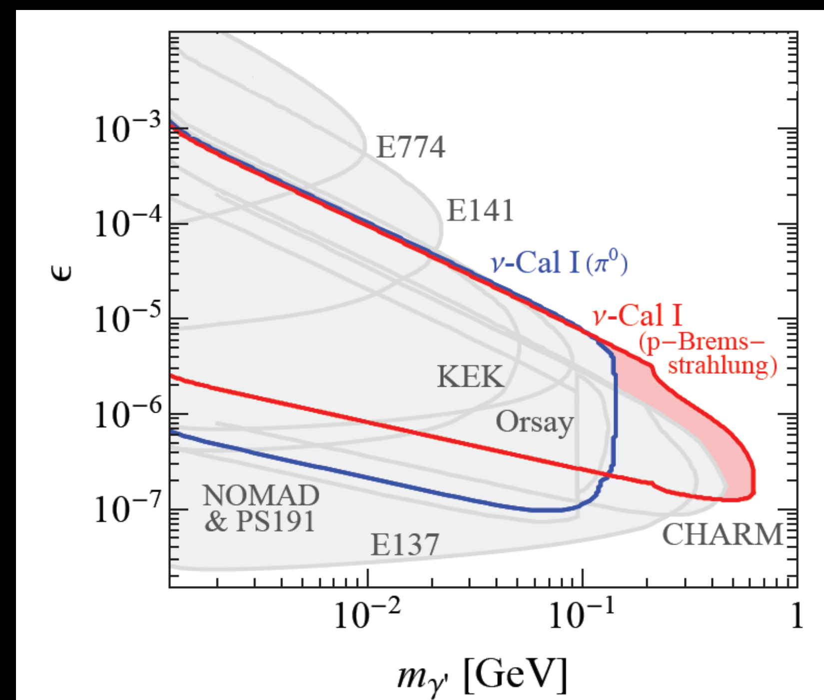
Other constraints and future initiatives

Beam dump experiments





Blumlein & Brunner, arXiv: 1311.3870



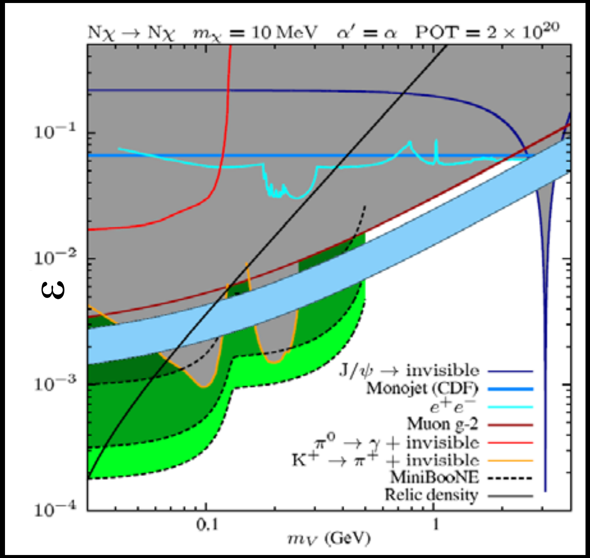
- Beam produces hadronic and/or EM shower
- Secondary particles emit A'
- Dark photons can decay near the detector, and be reconstructed as narrow resonances
- Original experiments looking for ν, axions, light Higgs,… have been reinterpreted as constraints on dark photon production
- Sensitive to low mixing values at large masses, complementary to other approaches

Beam dump and invisible A′ decays

Proton-beam

- Invisible DM produced in pion decay
- Neutrino factory ideal for probing this scenario (MicroBoone, Nova, LBNE,…)

E.g MiniBoone expected reach

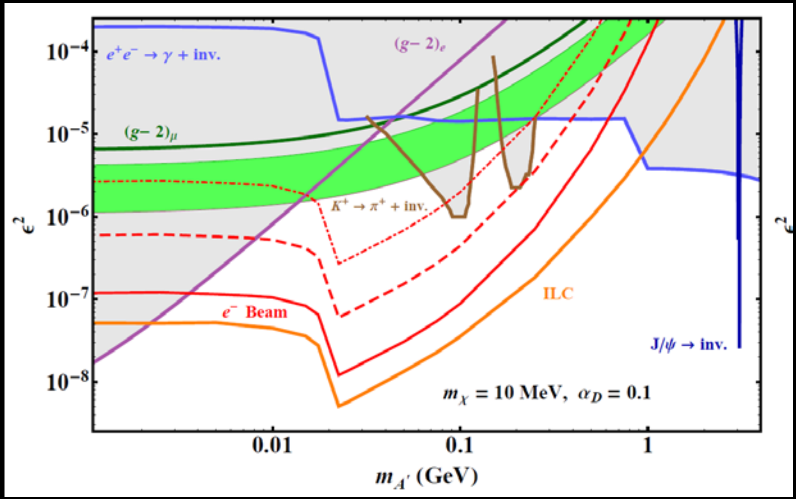


Aguilar-Arevalo *et al.*, arXiv:1211.2258

Electron-beam

- Low background
- Small mass detector
- Favorable kinematics

Izaguirre *et al.*, arXiv:1307.6554



Fixed target experiments

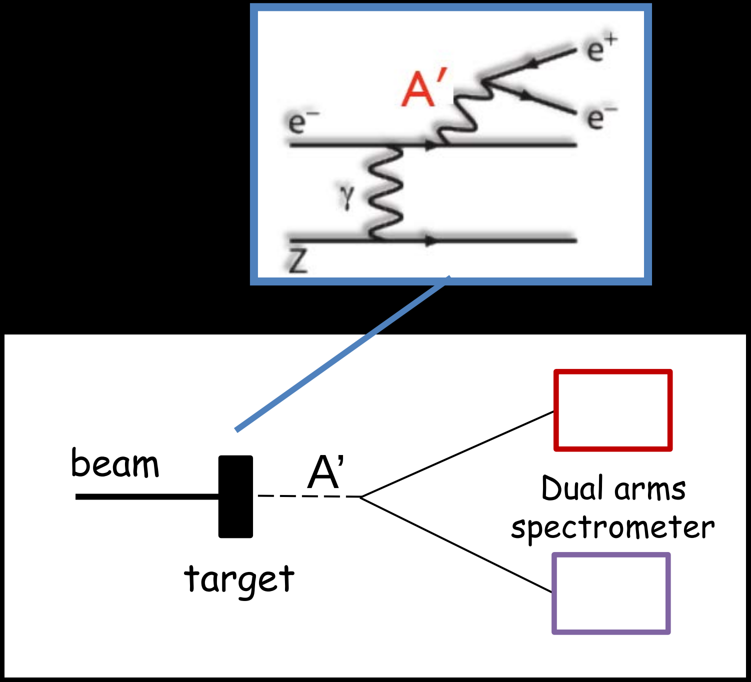
- Electron beam on fixed target radiates A'
- Decay product detected by dual arm spectrometer

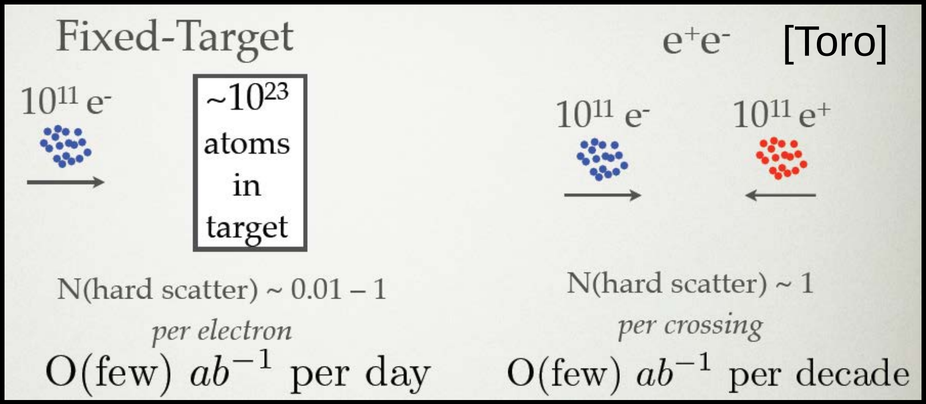
Fixed target have huge luminosity

- Much denser target
- Cross-section $\propto Z^2$ and $1/m^2$

But small signal and large background

- Small bump on top of background
- Displaced vertices boosts sensitivity





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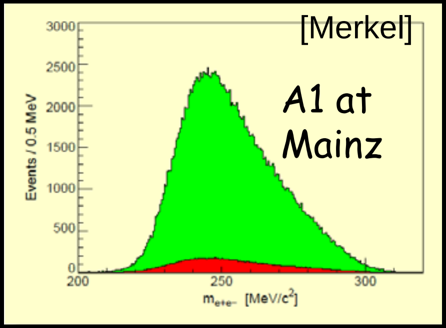
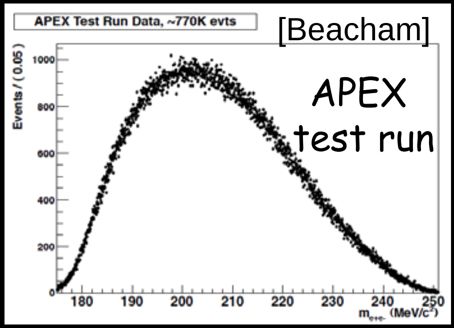
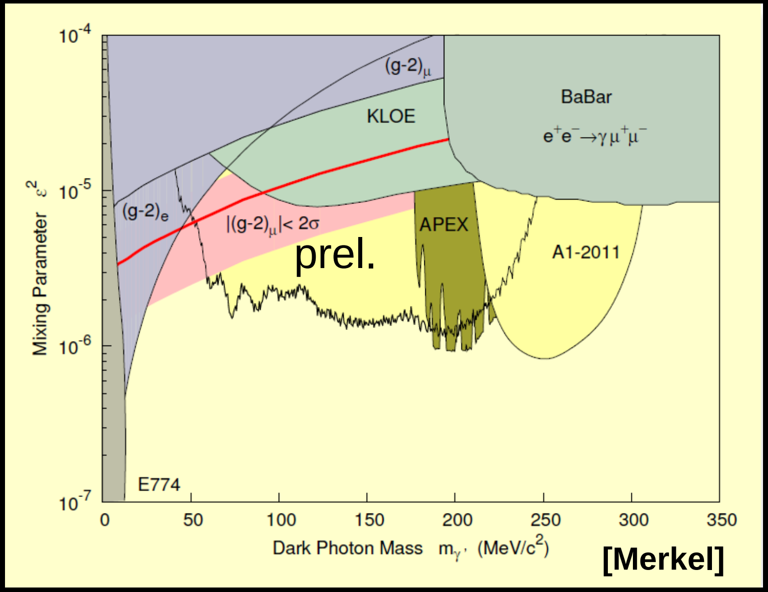
Recent results

- A1 at Mainz: 850 MeV e^- beam
- APEX at Jlab: 6 GeV e^- beam





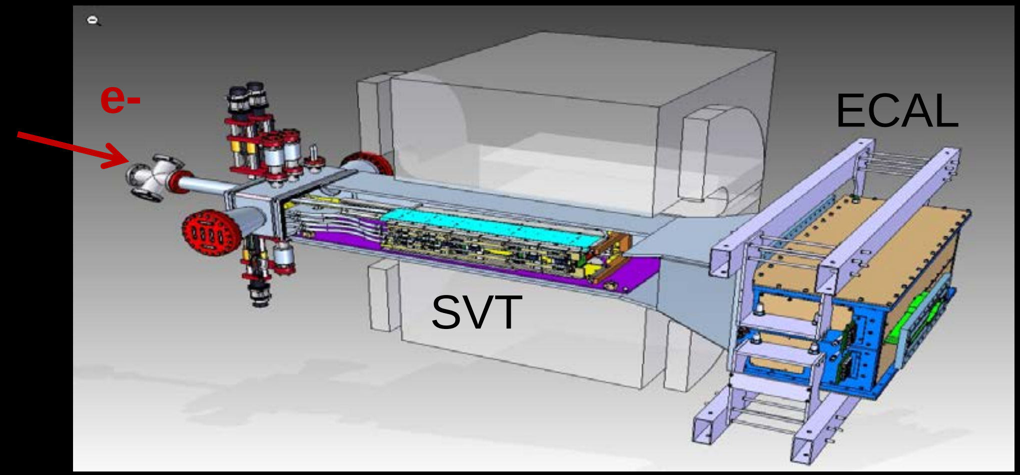


Expect to improve sensitivity in near future

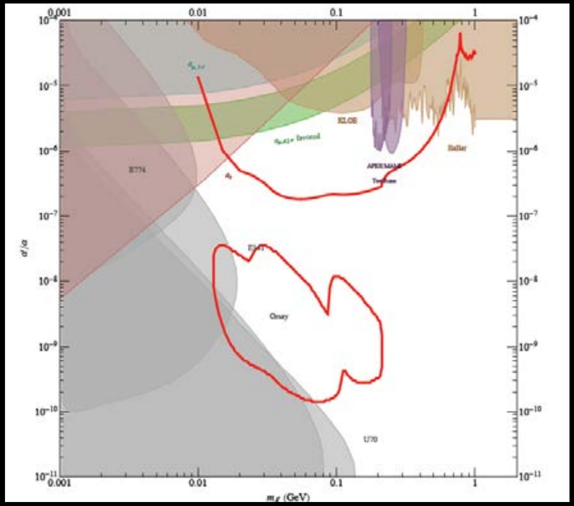
HPS proposal*

Heavy Photon Search experiment at JLab

- Large forward-acceptance spectrometer
- Silicon vertex tracker to measure e^+e^- mass and vertex position
- $PbWO_4$ crystal calorimeter to identify e^+e^- and trigger
- High rate trigger and DAQ
- Search for prompt and displaced A′ decays
- Test run in 2012 to validate the concept
- Should be running in 2014-2015



HPS expected reach (HPS proposal)



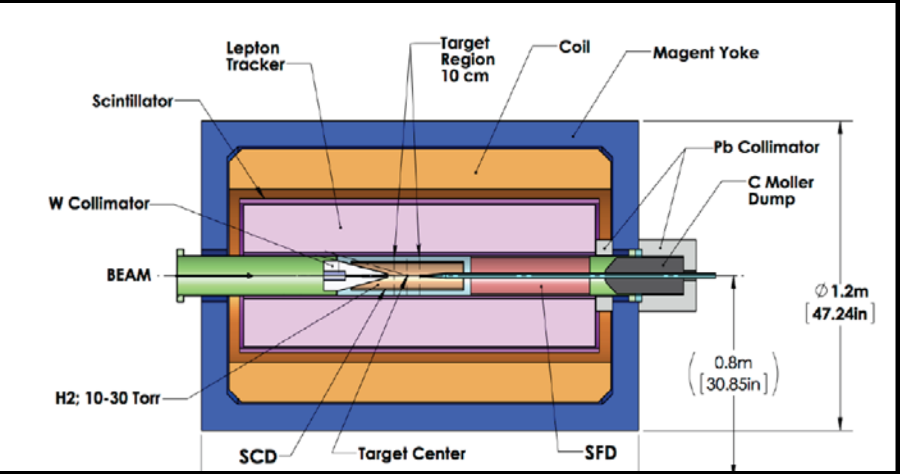
1 week 1.1 GeV
+3 weeks 2.2 GeV
+3 weeks 6.6 GeV

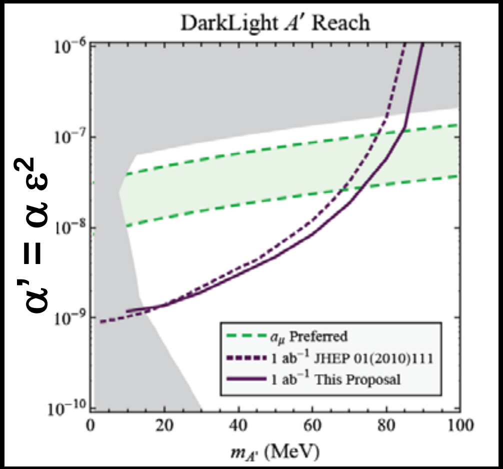
*https://confluence.slac.stanford.edu/display/hpsg/HPS+Proposals

DarkLight proposal

DarkLight* at Jlab

- Compact 4π detector
- Electron beam (100 MeV) on gaseous hydrogen target
- Measure the full reaction
  $e^- p \to e^- p A' \to e^- p \; e^+e^-$
- Measure visible and invisible A' decays for $m_{A'}$ < 90 MeV
- Test run at Jlab FEL to demonstrate concept
- Expect to run in 2016 (?)



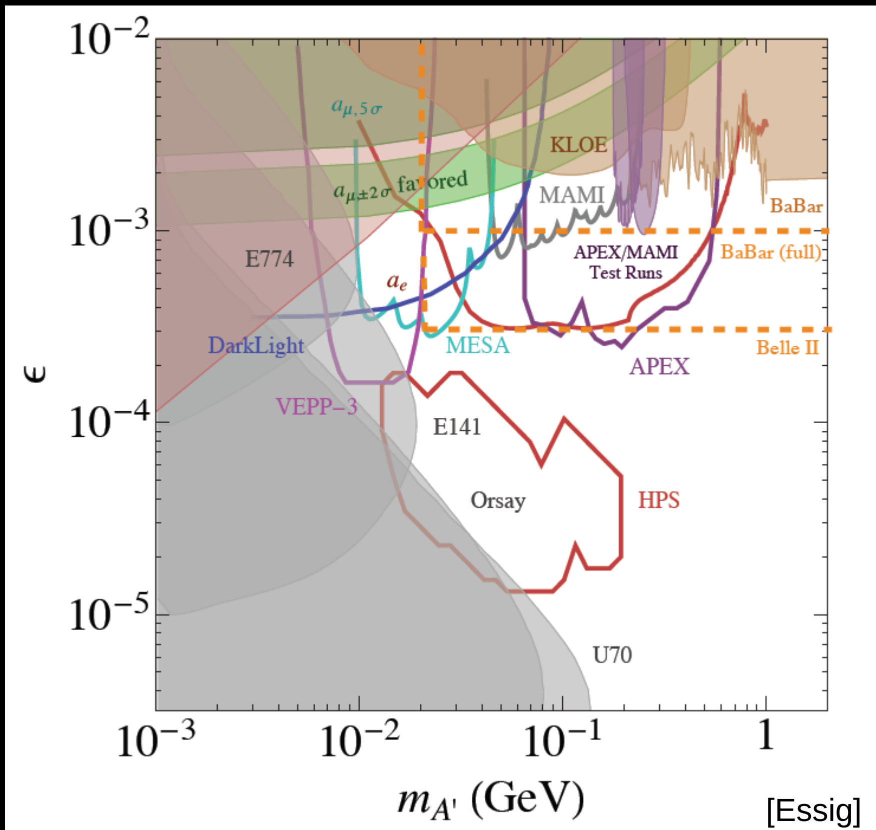


*DarkLight = Detecting A Resonance Kinematically with eLectrons Incident on a Gaseous Hydrogen Target

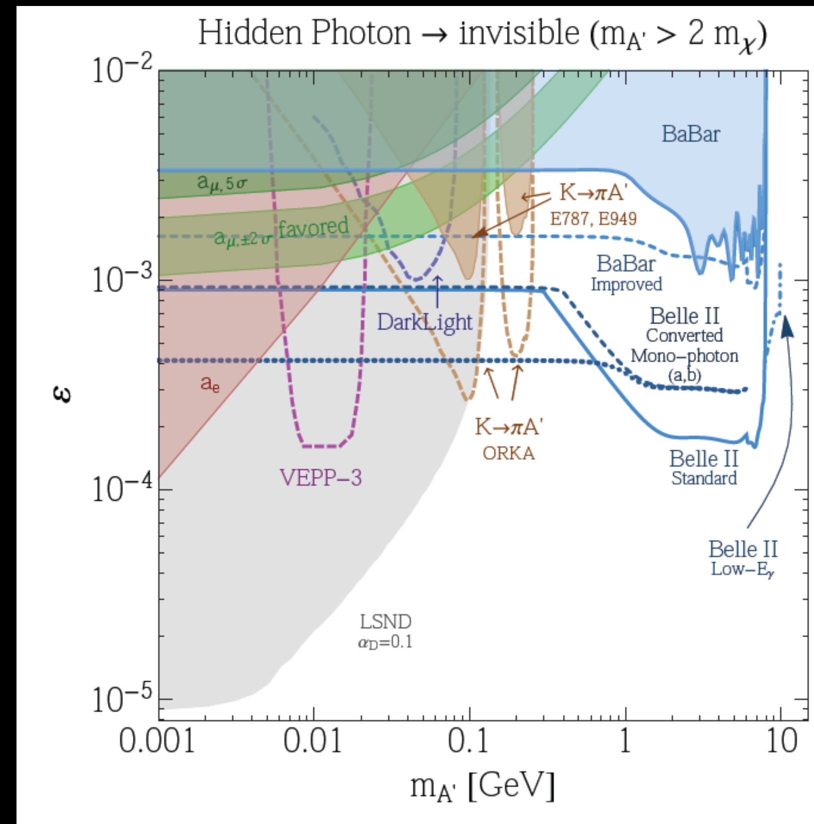
http://dmtpc.mit.edu/DarkLight/DarkLightProposal_PAC39.pdf

Future prospects

A’ → visible



A’ → invisible



Essig *et al.*, arXiv:1309.5084

Start probing parameter space, but still a large fraction of uncovered territory!

Summary

- Dark forces open a new window on physics far beyond the SM.
- In particular, a light dark sector as a dark matter candidate is well motivated by theory, astrophysics and particle physics measurements.
- A fraction of the allowed parameter space has already been probed by current experiments: g-2, fixed target, beam dump, e^+e^- colliders,…
- But there is still a lot of uncharted territory!
- Small-scale, inexpensive experiments at existing facilities will further explore this parameter space, hopefully resulting in a game-changing discovery.
- In other words, a possibility of huge payoff with small investment !

Thank you
for your attention

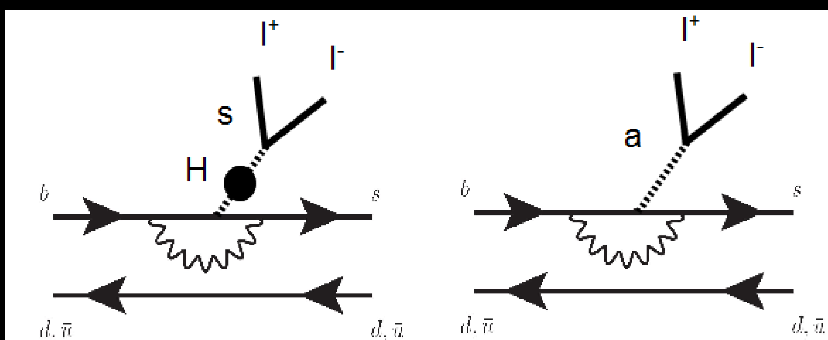
Extra material

Lowest dimensional operators connecting dark sectors to the SM
(higher dimensional operators are mass suppressed)

Vector	$\varepsilon F^{Y,\mu\nu} F'_{\mu\nu}$	Dark photon
Higgs	$\lambda H^2 S^2 + \mu H^2 S$	Exotic Higgs decays
Neutrino	$\kappa(HL)N$	Sterile neutrino
Axion	$f_a^{-1} F^{\mu\nu} F_{\mu\nu}\, a$	Axion / ALP

Batell et al., PRD 83 (2010) 054005

Scalar (s) and pseudo-scalar (a) content of a dark sector can be probed through the Higgs and axion portals in b → s transitions



Higgs portal	$H^{\dagger}H\,(AS + \lambda S^2)$
Axion portal	$f_{l,q}^{-1}\,\psi_{l,q}\gamma_{\mu}\gamma_5\psi_{l,q}\,\partial_{\mu} a$

Scalar - Higgs mixing angle

Phase-space

Form factor

$$\mathrm{Br}_{B\to KS} \simeq 4\times 10^{-7} \times \left(\frac{\theta}{10^{-3}}\right)^2 \mathcal{F}_K^2(m_S)\lambda_{KS}^{1/2}$$

$$\mathrm{Br}_{B\to K^*S} \simeq 5\times 10^{-7} \times \left(\frac{\theta}{10^{-3}}\right)^2 \mathcal{F}_{K^*}^2(m_S)\lambda_{K^*S}^{3/2}$$

$$\mathrm{Br}_{B\to Ka} \simeq 5\times 10^{-6} \times \left(\frac{100\ \mathrm{TeV}}{f_q}\ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_t}\right)\right)^2 \mathcal{F}_K^2(m_a)\lambda_{Ka}^{1/2}$$

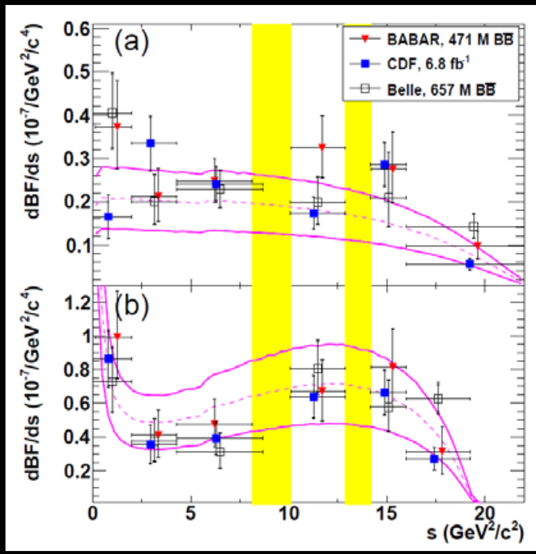
$$\mathrm{Br}_{B\to K^*a} \simeq 6\times 10^{-6} \times \left(\frac{100\ \mathrm{TeV}}{f_q}\ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_t}\right)\right)^2 \mathcal{F}_{K^*}^2(m_a)\lambda_{K^*a}^{3/2}.$$

Pseudoscalar - lepton(quark) coupling

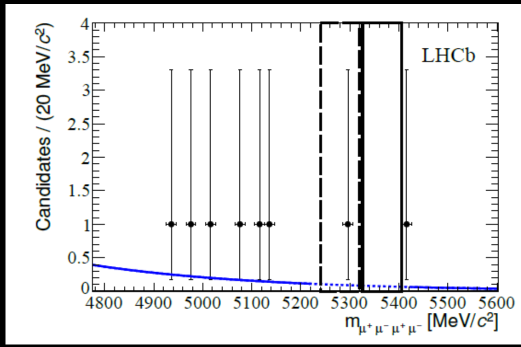
Batell et al., PRD 83 (2010) 054005

Unfortunately, no results yet, but…

$B \to K l^+ l^-$ (PRD 86 (2012) 032012)

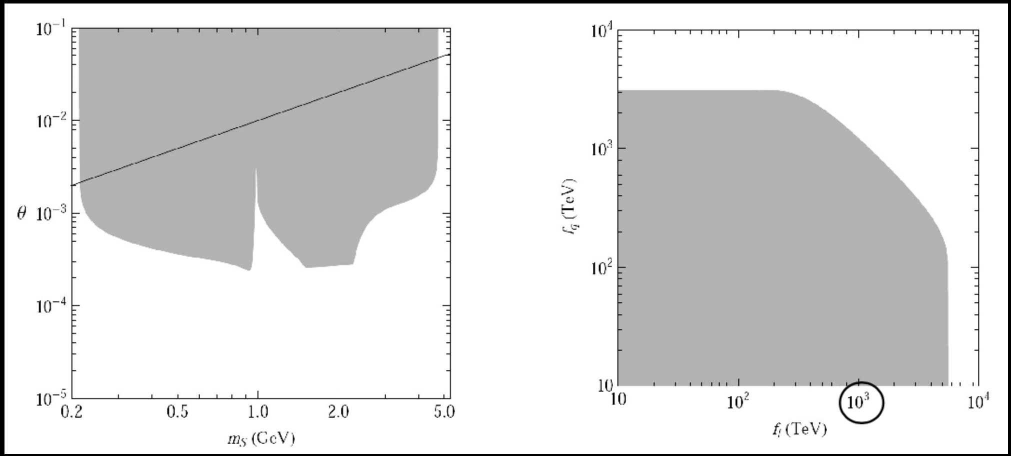


LHCb : $B \to \mu^+\mu^-\mu^+\mu^-$ (1 fb^{-1})



No sign of dimuon resonance

Expected limits for *BABAR* on scalar-Higgs mixing angle (θ) and pseudo-scalar couplings ($f_{l,q}$) assuming limits on BF($B \to K^{(*)} l^+l^-$) for a narrow l^+l^- (pseudo-)scalar at the level of ~10^{-8}



Limits on pseudo-scalar coupling could be set at the level of thousands of TeV

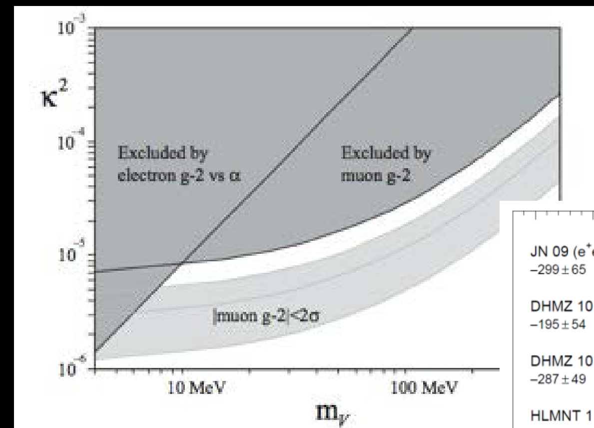
Precision measurement hints

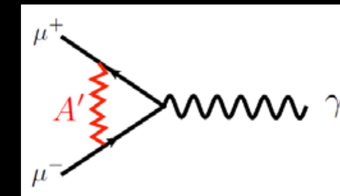
Muon g-2

Dark photon contribution with $\varepsilon \sim 10^{-3}$ could explain observed discrepancy.

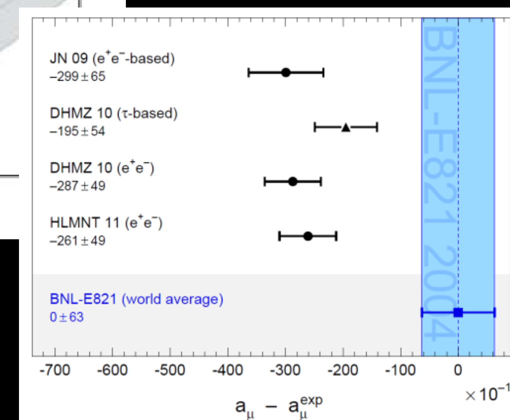
Most of the allowed parameter space has been recently excluded

M. Pospelov, PRD D 80, 095002 (2009)





PDG

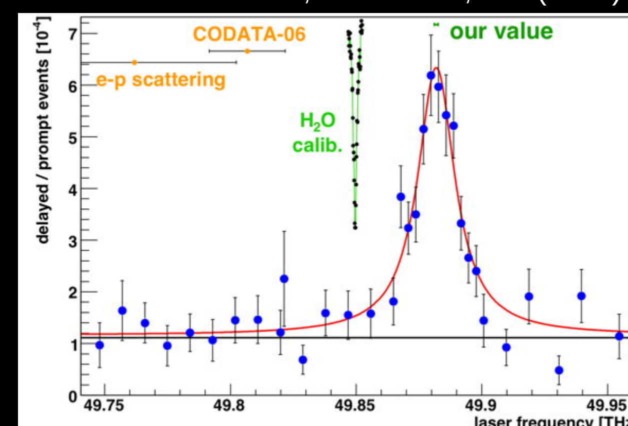


Muonic hydrogen

New light force carriers could explain the proton radius puzzle: discrepancy between the measurement by Lamb shift in muonic hydrogen and other methods (e^-p scattering, hydrogen spectroscopy)

Need couplings beyond kinetic mixing (lepton flavor-violating component)

R. Pohl et al., Nature **466**, 213 (2010)



Dark Higgs boson

PRL 108 (2012) 211801

Limits on the cross-section $e^+e^- \rightarrow A'^* \rightarrow h'$ A', $h' \rightarrow A' A'$ in the regime $m_H > 2m_{A'}$

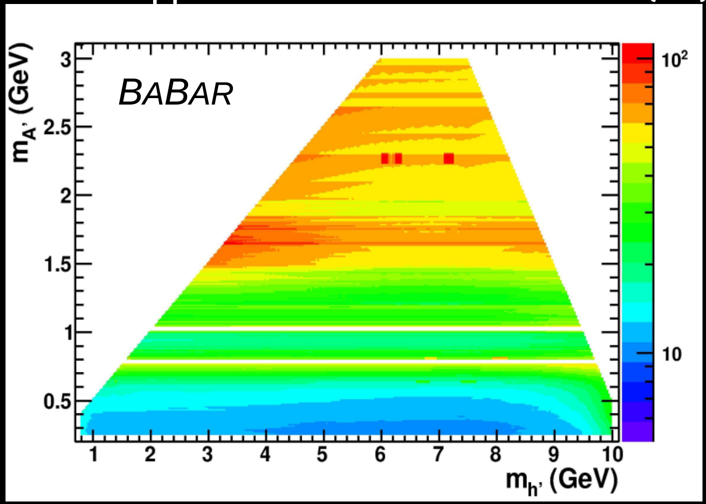
- Scan the m_h vs m_A plane, Bayesian limit with uniform prior in cross-section
- Conservative approach, treat every event as signal candidate (hot spots in bi-dimensional plot)
- Limits from 10 to ~100 ab

Extract limits[1] on the product $\alpha_D\varepsilon^2$

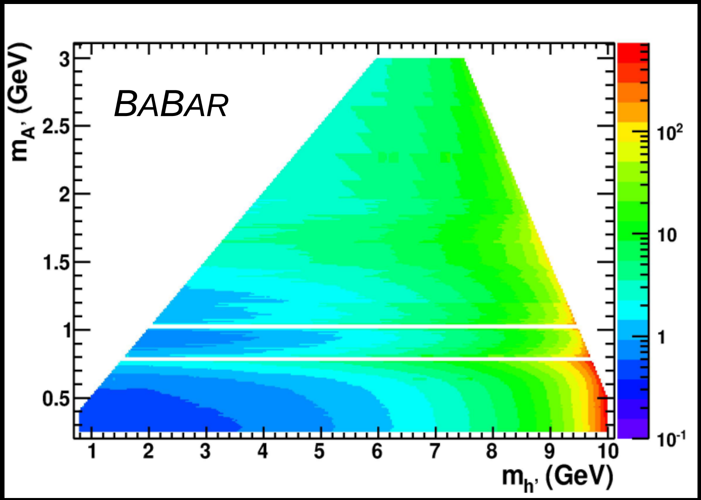
$$\sigma_{e^+e^-\rightarrow Vh'} = \frac{\pi\alpha\alpha'\kappa^2}{3s}\left(1-\frac{m_V^2}{s}\right)^{-2}\sqrt{\lambda\left(1,\frac{m_{h'}^2}{s},\frac{m_V^2}{s}\right)}\left[\lambda\left(1,\frac{m_{h'}^2}{s},\frac{m_V^2}{s}\right)+\frac{12m_V^2}{s}\right]$$

Limits down to a few x 10^{-10}

90% CL upper limits on cross-section (ab)



90% CL upper limits on $\alpha_D\varepsilon^2$ ($\times10^{-9}$)



1. B. Batell, M. Pospelov and A. Ritz, Phys.Rev.D79:115008,2009.